**High Energy Electron Injection (E-Beam) Technology for the
Ex-Situ Treatment of MtBE-Contaminated Groundwater**

Innovative Technology Evaluation Report

By

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FOREWORD

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E. Timothy Oppelt, Director
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ABSTRACT

This Innovative Technology Evaluation Report documents the results of a demonstration of the high-energy electron injection (E-Beam) technology in application to groundwater contaminated with methyl t-butyl ether (MtBE) and with benzene, toluene, ethylbenzene, and xylenes (BTEX). The E-beam technology destroys organic contaminants in groundwater through irradiation with a beam of high-energy electrons. The demonstration was conducted at the Naval Base Ventura County (NBVC) in Port Hueneme, California.

Results of two weeks of steady state operation at an E-beam dose of 1,200 kilorads (krads) indicated that MtBE and BTEX concentrations in the effluent were reduced by greater than 99.9 percent from influent concentrations that averaged over 1,700 µg/L MtBE and 2,800 µg/L BTEX. Further, the treatment goals for the demonstration, which were based on drinking water regulatory criteria, were met for all contaminants except for *t*-butyl alcohol (tBA), a degradation product of MtBE. Dose experiments indicated that tBA was not consistently reduced to below the treatment goal of 12 µg/L although the results indicated that tBA by-product formation decreased as dose increased. Thus, it is possible that, at increased energy input beyond that tested in the demonstration, the E-Beam technology might have met the prescribed treatment objectives for TBA. Acetone and formaldehyde were the two most prevalent organic by-products that were formed by E-beam treatment, with mean effluent concentrations during the two-week steady state testing of 160 and 125 µg/L, respectively. Bromate was not formed during E-beam treatment.

An economic analysis of the E-beam treatment system indicated that the primary costs are for the E-beam equipment and for electrical energy. The estimated cost ranged from over $40 per 1000 gallons for a small-scale remedial application to about $1.00 per 1000 gallons for a larger-scale drinking water application.

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ACRONYMS AND ABBREVIATIONS

ACL	Alternate concentration limits
AEA	Atomic Energy Act
AL	Action level
ARAR	Applicable or relevant and appropriate requirement
BTEX	Benzene, toluene, ethylbenzene, and xylenes
CAA	Clean Air Act
CERCLA	Comprehensive Emergency Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
Cl^-	Chloride ion
CO_2	Carbon dioxide
COD	Chemical oxygen command
CWA	Clean Water Act
DBPR	Disinfection By-product Rule
1,2-DCE	1,2-Dichloroethene
DHS	Department of Health Services
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DOE	Department of Energy
e^-_{aq}	Aqueous electrons
E-Beam	High energy electron injection
EPA	U.S. Environmental Protection Agency
gpm	Gallons per minute
HAA	Haloacetic acid
HVEA	High Voltage Environmental Applications, Inc.
H_2	Hydrogen
H_2O_2	Hydrogen peroxide
$\bullet H$	Hydrogen atom
H_3O^+	Hydronium ion
ICAL	Initial calibration
ITER	Innovative Technology Evaluation Report
Krads	Kilorads
kV	Kilovolts
kW	Kilowatts
kWh	Kilowatt hours
LCS/LCSD	Laboratory control samples and laboratory control sample duplicates
LDR	Land Disposal Restriction
mA	Milliamps
MCL/MCLG	Maximum Contaminant Level and Maximum Contaminant Level Goal
MDL	Method detection limit
µg/L	Micrograms per liter
mg/L	Milligrams per liter
mm	Millimeters
MS/MSD	Matrix spike/matrix spike duplicate
MtBE	Methyl-t-butyl ether
NAAQS	National Ambient Air Quality Standards

ACRONYMS AND ABBREVIATIONS (Continued)

NBVC	Naval Base Ventura County
NDMA	N-nitrosodimethylamine
NESHAP	National Emission Standards for Hazardous Air Pollutants
NEX	Naval Exchange
NFESC	Naval Facilities Engineering Service Center
NOEL	No observable effect level
NPDES	National Pollutant Discharge Elimination System
NRMRL	National Risk Management Research Laboratory
NSPS	New Source Performance Standards
•OH	Hydroxyl radical
OSWER	Office of Solid Waste and Emergency Response
PAH	Polynuclear aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PCE	Tetrachloroethene
POTW	Publicly owned treatment works
PPE	Personal protection equipment
ppm	Parts per million
PVC	Polyvinyl chloride
QA	Quality assurance
QAPP	Quality assurance project plan
QC	Quality Control
QCC	Quality Control Coordinator
RCRA	Resource Conservation and Recovery Act
RRF	Relative response factor
RPD	Relative percent difference
RSD	Relative standard deviation
RTD	Resistance temperature device
SDS	Simulated distribution system
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SVOC	Semi-volatile organic compound
tBA	t-Butyl alcohol
TCE	Trichloroethene
TEP	Technology evaluation plan
TOC	Total organic carbon
TSCA	Toxic Substances Control Act
TTHM	Total trihalomethanes
TSA	Technical systems audit
UCL	Upper confidence limit
UFC	Uniform formation conditions
VOA	Volatile organic analysis
VOC	Volatile organic compound
WQS	Water quality standard

EXECUTIVE SUMMARY

The high-energy electron injection (E-Beam) technology destroys organic contaminants in groundwater through irradiation with a beam of high-energy electrons. The injection of accelerated electrons into an aqueous solution results in the formation of three primary reactive species: aqueous electrons (e^-_{aq}) and hydrogen radicals ($\bullet H$), which are strong reducing species; and hydroxyl radicals ($\bullet OH$), which are strong oxidizing species. These reactive species can destroy most organic compounds to non-detectable concentrations. However, oxidation by-products such as acetone, aldehydes, and glyoxals, may be formed in significant concentrations.

The capabilities of the E-Beam technology for treating groundwater contaminated with methyl *t*-butyl ether (MtBE) and with benzene, toluene, ethylbenzene, and xylenes (BTEX) was demonstrated by Haley and Aldrich in the summer and fall of 2001. The site that was selected for the demonstration was the source zone of the Naval Exchange Gasoline Station site at the Naval Base Ventura County in Port Hueneme, California. Treatment goals were established for the demonstration based primarily on California maximum contaminant levels (MCL) for drinking water.

The demonstration of the E-Beam technology was implemented in two phases, including a two-week steady-state operation at an E-beam dose of 1,200 kilorads (krad) and a shorter series of tests in which the E-Beam dose was varied from 800 to 1,600 krad. During the demonstration, grab samples of the groundwater were collected before and after treatment at the E-Beam influent and effluent sampling locations and analyzed for volatile organic compounds (VOC), aldehydes/glyoxals, bromate, and general water quality variables.

Results of the two-week steady-state operation indicated that MtBE and BTEX concentrations in the effluent were reduced by greater than 99.9 percent from influent concentrations that averaged over 1,700 µg/L MtBE and 2,800 µg/L BTEX. Further, the 95 percent upper confidence level for the mean effluent concentrations of MtBE, benzene, and toluene were below the corresponding treatment goals of 5 µg/L, 1 µg/L, and 150 µg/L, respectively; neither ethylbenzene nor xylenes were detected in the effluent. However, effluent concentrations of *t*-butyl alcohol (tBA), a degradation product of MtBE, were consistently several times the treatment goal of 12 µg/L.

Results of the dose experiments indicated that a dose of 800 krads was not quite sufficient to bring the concentration of MtBE to below the treatment goal of 5.0 µg/L, but higher doses were effective in meeting this treatment goal. However, tBA was not consistently reduced to below the treatment goal of 12 µg/L even at the highest dose (1,600 krads), although the results from the dose-response experiment indicated that tBA by-product formation decreased as dose increased. Thus, it is possible that, at increased energy input beyond that tested in the demonstration, the E-Beam technology might have met the prescribed treatment objectives for TBA.

A number of organic by-products were measured in effluent samples, including acetone, acetaldehyde, formaldehyde, glyoxal, and methyl glyoxal. Acetone and formaldehyde were the two most prevalent organic by-products, with mean effluent concentrations during the two-week steady-state testing of 160 and 125 µg/L, respectively. Bromate concentrations were near the

detection limit of 1 µg/L in both influent and effluent samples; therefore, bromate does not appear to be a by-product of E-beam treatment.

An economic analysis of the E-beam treatment system was conducted for two applications: a groundwater remedial application at a flow rate of 10 gallons per minute, and a larger-scale drinking water treatment application at a flow rate of 10 million gallons per day. The primary costs in both applications were for the E-beam equipment and for electrical energy. For the remedial application, the overall cost was estimated to be over $40 per 1000 gallons, while for the larger-scale drinking water application the overall cost was estimated to be about $1.00 per 1000 gallons. The lower unit cost for the larger-scale drinking water application resulted from economies of scale and the assumption that much lower influent concentrations of MtBE would be treated in such an application.

1 INTRODUCTION

The high energy electron injection (E-Beam) technology developed by High Voltage Environmental Applications, Inc. (HVEA) was demonstrated by Haley and Aldrich, Inc. for the treatment of groundwater contaminated with methyl *t*-butyl ether (MtBE) at the Naval Base Ventura County (NBVC) in the summer and fall of 2001. This Innovative Technology Evaluation Report (ITER) describes the results of that demonstration and provides other pertinent technical and cost information for potential users of this technology. For additional information about this technology, and the evaluation site, refer to key contacts listed at the end of this section.

1.1 Purpose and Organization of the ITER

Information presented in the ITER is intended to assist decision-makers in evaluating specific technologies for treatment of contaminated media. The ITER represents a critical step in the development and commercialization of a treatment technology. The report discusses the effectiveness and applicability of the technology and analyzes costs associated with its application. The technology's effectiveness is evaluated based on data collected during the demonstration. The applicability of the technology is discussed in terms of waste and site characteristics that could affect technology performance, material handling requirements, technology limitations, and other factors.

The purpose of this ITER is to present information that will assist decision-makers in evaluating the E-Beam technology for application to a particular site cleanup and for the treated water to be considered as a source of drinking water. This report provides background information and introduces the E-Beam technology (Section 1.0), analyzes the technology's applications (Section 2.0), analyzes the economics of using the E-Beam technology to treat contaminated groundwater (Section 3.0), provides an overview and evaluation of the E-Beam demonstration at the NBVC (Section 4.0), summarizes the technology's status (Section 5.0), and presents a list of references used to prepare the ITER (Section 6.0). Vendor's claims for the E-Beam technology are presented in Appendix A.

1.2 Description of the MtBE Demonstration Program

In 1999, the U.S. Environmental Protection Agency (EPA) and the U.S. Navy entered into a memorandum of understanding to conduct a multi-year program involving demonstration and evaluation of several innovative technologies for treatment of MtBE in groundwater. Technology vendors were identified through an open solicitation requesting proposals for processes to treat MtBE. Vendors participating in the program were selected based on the results of external and internal EPA/Navy peer reviews.

The site that was selected for the multiple-vendor MtBE demonstration program was the source zone of the Naval Exchange (NEX) Gasoline Station site, located at the NBVC, Port Hueneme, California. The NEX Gasoline Station site is typical of similar gasoline service station sites throughout the country, where leaking gasoline storage tanks and product delivery lines have contaminated surrounding groundwater with gasoline components and additives, including MtBE. The MtBE plume that emanates from the NEX Gasoline Station at the NBVC site extends

approximately 5,000 feet from the contamination source in a shallow perched aquifer (SCS and Landau Associates 1985).

Three locations within the MtBE plume at the NEX Gasoline Station site were identified as potential locations for technology demonstrations. These three locations are differentiated by their distance from the source and are identified as follows:

1. **Source Zone**: This zone is closest to the source, contains high concentrations of MtBE as well as benzene, toluene, ethylbenzene, and xylenes (BTEX), and potentially contains free-phase gasoline.

2. **Middle Zone**: This zone is the area mid-way down gradient along the MtBE plume contains moderate concentrations of MtBE; no BTEX or free-phase gasoline is known to be present.

3. **Wellhead Protection Zone**: This zone is farthest down gradient along the plume, and contains MtBE at lower concentrations than the first two zones.

Figure 1-1 indicates the extent of the MtBE plume at Port Hueneme as of August, 1999 and identifies the three zones within the plume; Figure 1-2 provides an expanded view of the Source Zone, the location of the E-Beam technology demonstration.

Figure 1-1 Site Locations at NBVC Port Hueneme

23rd
Ave.

Credit Union 1336

Heritage
Park

N

NEX
Gasoline
Station

NFESC/Equilon/ASU In-Situ Bioremediation.

Extraction Zone (250')

S-

S-2

S-3
(CBC-21)

S-4

S-5

E-Beam
Demonstration
Area

Air Sparge Site1

Source Zone MtBE Plume

Harris Street

Air Sparge Site2

Figure 1-2   Source Zone Site Locations
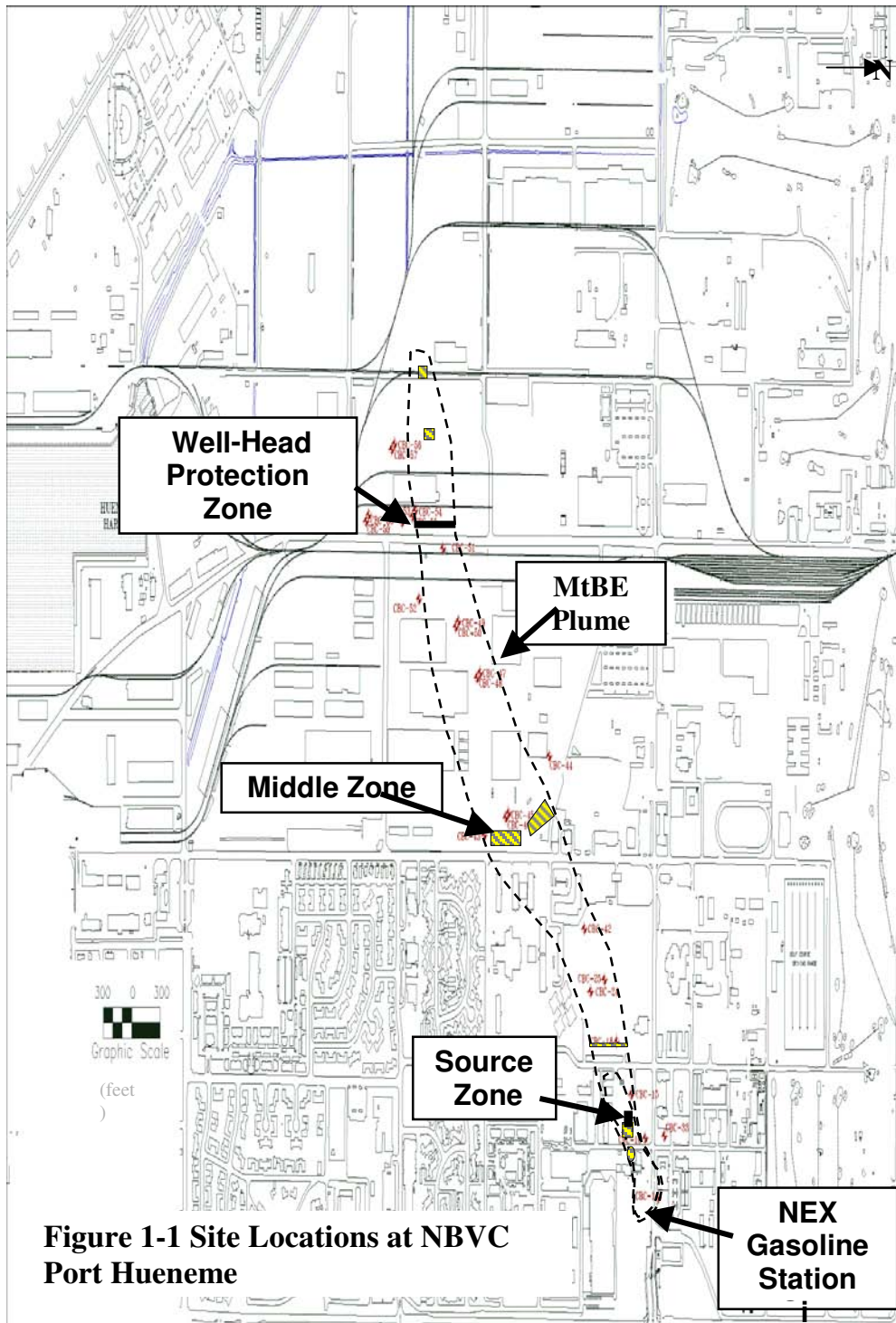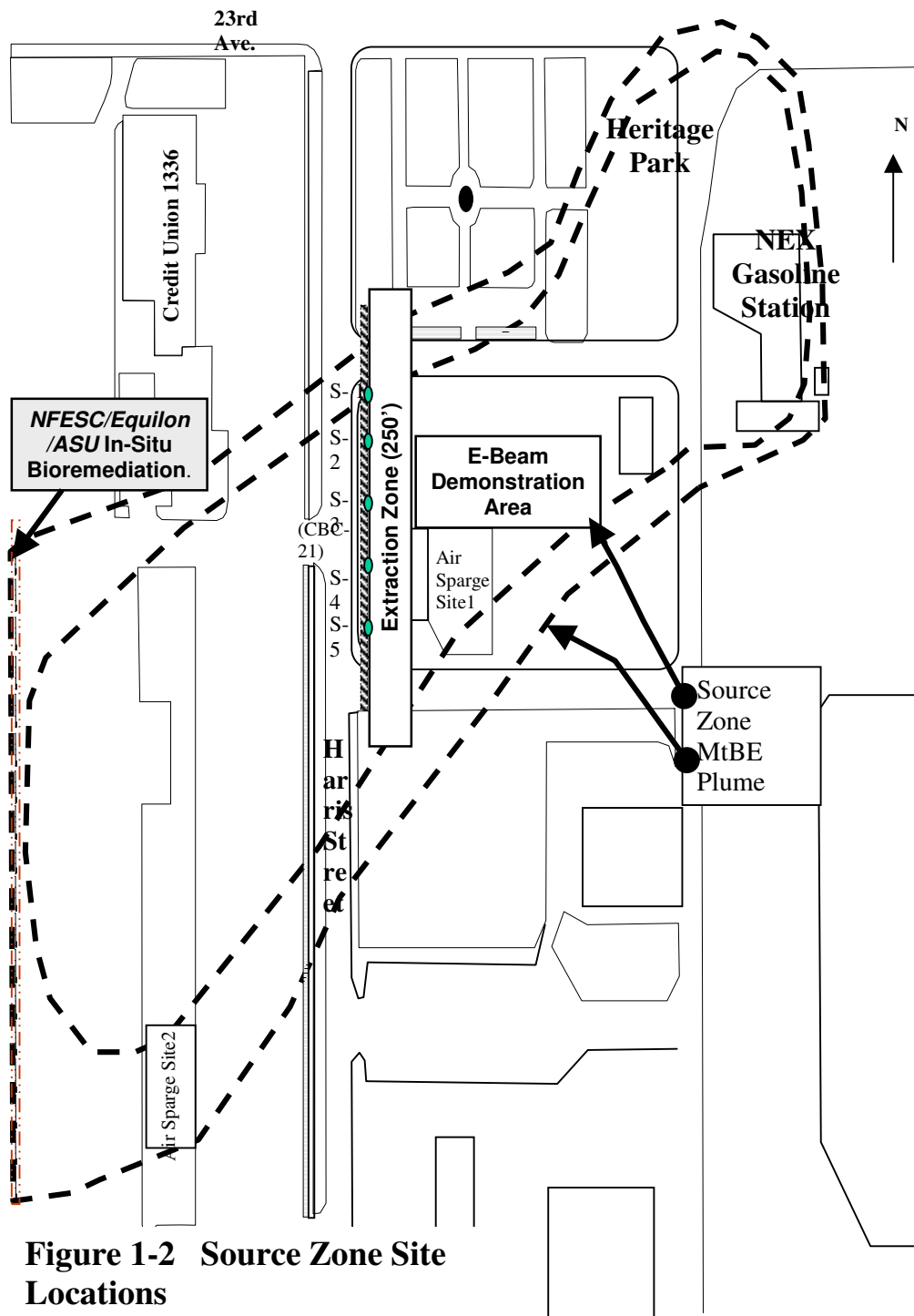
1.3   Technology Description

This section describes the HVEA E-Beam technology that was operated by Haley and Aldrich, Inc. and demonstrated at the NBVC, Port Hueneme, California.

1.3.1   Principles of the E-Beam Technology

The E-Beam technology destroys organic contaminants in groundwater through irradiation with a beam of high-energy electrons. The injection of accelerated electrons into an aqueous solution results in the formation of reactive species described by equation 1 (Buxton et al., 1988):

$$H_2O \text{ -}/\text{W}\text{\textbackslash} \rightarrow (2.7) \, OH, \, (0.6) \, \underset{\cdot}{H}, \, (2.6) \, e^-_{aq}, \, (0.45) \, H_2, \, (0.7) \, H_2O_2, \, (2.6) \, H_3O^+ \qquad [1]$$
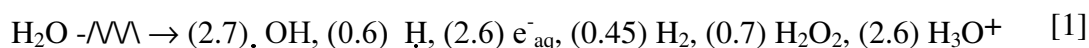
The numbers in parentheses denote the yield (G-value) of each species per 100 eV absorbed dose (energy). This can be thought of as an efficiency estimate, that is, the relative concentration of a radical, excited species, or molecule per unit-absorbed energy.

During irradiation of water, three primary transient reactive species are formed: aqueous electrons (e^-_{aq}) and hydrogen radicals (•H), which are strong reducing species; and hydroxyl radicals (•OH), which are strong oxidizing species. These reactive species can destroy organic compounds initially present in water at part-per-million (ppm) concentrations, in most cases, to non-detectable concentrations. Because three reactive species are formed, there are multiple mechanisms or chemical pathways for organic compound destruction. In this way, the E-Beam technology differs from other technologies that involve free radical chemistry, which typically rely on a single reactive species in the organic compound destruction mechanism, usually •OH. The entire sequence of reactions between organic compounds and reactive species occurs in the area where the E-Beam impacts the water and is completed in milliseconds. As high-energy electrons impact flowing water, the electrons slow down, lose energy, and react with water to produce the three reactive species responsible for organic compound destruction, as well as hydrogen (H_2), hydrogen peroxide (H_2O_2), and hydronium ions (H_3O^+).

Equation 1 shows that the •OH and e^-_{aq} account for about 90 percent of the three primary reactive species formed by the E-Beam. According to published results and computer models provided by Haley and Aldrich that simulate radiation chemistry in water, some compounds are preferentially destroyed by either •OH or e^-_{aq}. For example, chlorinated hydrocarbons such as chloroform are dechlorinated by a reaction with e^-_{aq} that initiates a series of subsequent reduction and oxidation reactions leading to hydrocarbon mineralization. Other organic compounds undergo a variety of reactions, including addition, hydrogen abstraction, electron transfer, and radical-radical combination. For example, the BTEX compounds are initially destroyed primarily through •OH initiated reactions.

The E-Beam is produced using an electron accelerator. Within the electron accelerator, a stream of electrons is emitted when an electric current (beam current) is passed through a tungsten wire filament. The electron stream is accelerated by applying an electric field and is focused into a beam using collimating plates. The applied voltage determines the energy (speed) of the accelerated electrons, which affects the depth to which the E-Beam penetrates the water

being treated. The number of electrons emitted per unit time is proportional to the beam current; therefore, the E-Beam power is the product of the beam current and the accelerating voltage.

Dose is the amount of energy from the E-Beam that is absorbed by the irradiated water per unit mass. Dose is expressed in kilorads (krads); a krad is defined as 10^5 ergs of absorbed energy per gram of material. The dose depends on (1) the density and thickness of the water stream; (2) E-Beam power, which is a function of current and accelerating voltage; and (3) the amount of time the water is exposed to the E-Beam, which depends on the flow rate of the water. Dose is the principal operating parameter that affects the performance of the E-Beam technology.

The E-Beam treatment technology does not generate residue, sludge, or spent media that require further processing, handling, or disposal. Target organic compounds are either mineralized or broken down into lower molecular weight compounds. It has been shown that the E-Beam produces transient, reactive species that react with contaminants to produce intermediate chemical species that are ultimately oxidized to carbon dioxide (CO_2), water, and salts. At low to intermediate doses, however, incomplete oxidation may result in the formation of unwanted chemical by-products such as low molecular weight aldehydes, organic acids, and semi-volatile organic compounds (SVOC). A number of reports have recently been published that detail this chemistry (Cooper et al., 2000; 2001;Hardison et al., 2002; Kim et al., 2002; Mezyk et al., 2001; O'Shea et al., 2001; 2002; Tornatore et al., 2000; Wu et al., 2002).

Haley and Aldrich notes that these by-products may include formaldehyde, acetaldehyde, glyoxal, and formic acid. In a recent demonstration of the technology in application to groundwater contaminated with trichloroethene (TCE) and tetrachloroethene (PCE), the vendor claims that aldehydes were formed at concentrations that accounted for less than 1 percent of the total organic carbon (TOC) content (Cooper et al., 1993). The vendor claims that at low doses (50 krads), formic acid accounted for up to 10 percent of the TOC content; however, this percentage decreased at higher doses (greater than 200 krads). According to the vendor, chloride ion (Cl^-) mass balances indicated that complete conversion of organic chlorine to Cl^- occurred during treatment. Additional research indicates that haloacetic acids, such as chloroacetic acid, may be formed (Gehringer et al., 1988).

1.3.2 Description of E-Beam Process

A diagram of the E-beam system that was used for the demonstration is shown in Figure 1-3. The E-beam system is housed in an 8-foot by 48-foot trailer and is rated for a maximum flow rate of 40 gallons per minute (gpm). The E-beam system is composed of the following components: a strainer basket, an influent pump, the E-beam unit, a cooling air processor, a blower, and a control console (not shown in Figure 1-3). These components are situated in three separate rooms: the pump room, process room, and control room. The pump room contains all ancillary equipment for both water and air handling; the radiation-shielded process room contains the E-beam unit itself; and the control room contains the control console where system-operating conditions are monitored and adjusted.

For the demonstration, the influent pump transferred contaminated groundwater from the five wells in the groundwater extraction zone to the E-beam unit. A strainer basket located upstream from the influent pump removed particulate matter greater than 0.045 inch in size from

the groundwater to prevent damage to the influent pump and other components of the treatment system.

The E-beam unit is composed of the following components: an electron accelerator, a scanner, a contact chamber, and lead shielding. The electron accelerator used for the demonstration is capable of generating an accelerating voltage of 500 kilovolts (kV) and a beam current of between 0 and 42 milliamps (mA). The accelerating voltage determines the E-beam penetration depth. Based on the maximum accelerating voltage and beam current that the electron accelerator can generate, the E-beam unit has a maximum power rating of 21 kW.

A scanner located beneath the electron accelerator uses magnetic coils to deflect the E-beam, causing it to scan into a prescribed shape and penetrate the flowing water (the E-beam scanner operation is similar to the vacuum tube in a television set). Contaminated groundwater is pumped through the contact chamber, which is located beneath the scanner. The scanner is operated in such a way that the E-beam contacts the entire surface of the water flowing through the contact chamber.

Two titanium membranes/windows separate the scanner from the contact chamber. The first (primary) window maintains a vacuum in the scanner and the second (secondary) titanium window isolates cooling air from the contact chamber; as the E-beam passes through the primary titanium window, a small amount of the E-beam's energy is absorbed by the window. This energy absorption is manifested in the form of heat. Because of the E-beam's high energy and operation in a confined space, at high power the titanium window may experience undesired heating. Passing recirculating cooling air between the primary and secondary windows cools the titanium window. Cooling air exiting from between the two windows flows through a cooling air processor, which includes a water-jacketed air chiller, and is then returned to re-cool the primary window by a blower.

Ozone, which is formed in the closed loop cooling air when it is exposed to the E-beam, is destroyed by the high discharge temperature (around 300° F) of the blower, according to Haley and Aldrich. Ozone is present in the cooling air return lines, which operate under a slight vacuum, until passing through the blower. However, the ozone concentration in the cooling air return lines is not routinely monitored because the cooling air system is a "closed loop" system, and ultimately the ozone is destroyed as the cooling air is heated by the blower.

Incidental leakage from the cooling system or atmospheric air present in the confined delivery system tends to create a buildup of ozone in the air space under the lead shielding. A vent system and associated ozone destruction unit (not shown in Figure 1-3) was installed to vent this ozone buildup, destroy it, and exhaust the heated air from the trailer. When the E-beam system is operating, both the influent pump and the blower run continuously. If either water or cooling airflow stops, the system automatically shuts down. Lead shielding surrounds the E-beam unit to prevent incidental X-ray emissions. X-rays are formed when the E-beam contacts various internal stainless steel surfaces. As an added safety measure, the process room is inaccessible and interlocked to shut down in the event of entry during system operation.

Resistance temperature devices (RTD) are used to measure the temperature of groundwater before and after treatment. The change in water temperature induced by application

of the E-Beam is the method to determine the E-beam dose. The water temperature is expected to increase by about 1°C to 3°C during treatment, depending on the E-Beam dose. The RTDs have a sensitivity of 0.1°C. A relationship between dose and beam current has been established, and the beam current is used for operational control of the system.

The contaminated groundwater flow rate is adjusted in the pump room, using the system's positive displacement influent pump and variable speed drive and is measured by a flow meter. The rotameter-type flow meter installed in the trailer has a 0 to 20 gpm working range. The cooling-air flow rate was determined by the manufacturer of the electron accelerator. Operationally, it is monitored by measuring the pressure drop across the contact chamber. The pressure drop is displayed on the control panel.

Influent and effluent water sampling ports are installed in the trailer-mounted E-Beam system for purposes of sampling untreated and treated water, as shown in Figure 1-3. The 500-gallon influent storage tank was not used during the demonstration except for start-up operations and to check the flow meter for accuracy.

FIGURE 1-3
E-BEAM TREATMENT SYSTEM SCHEMATIC
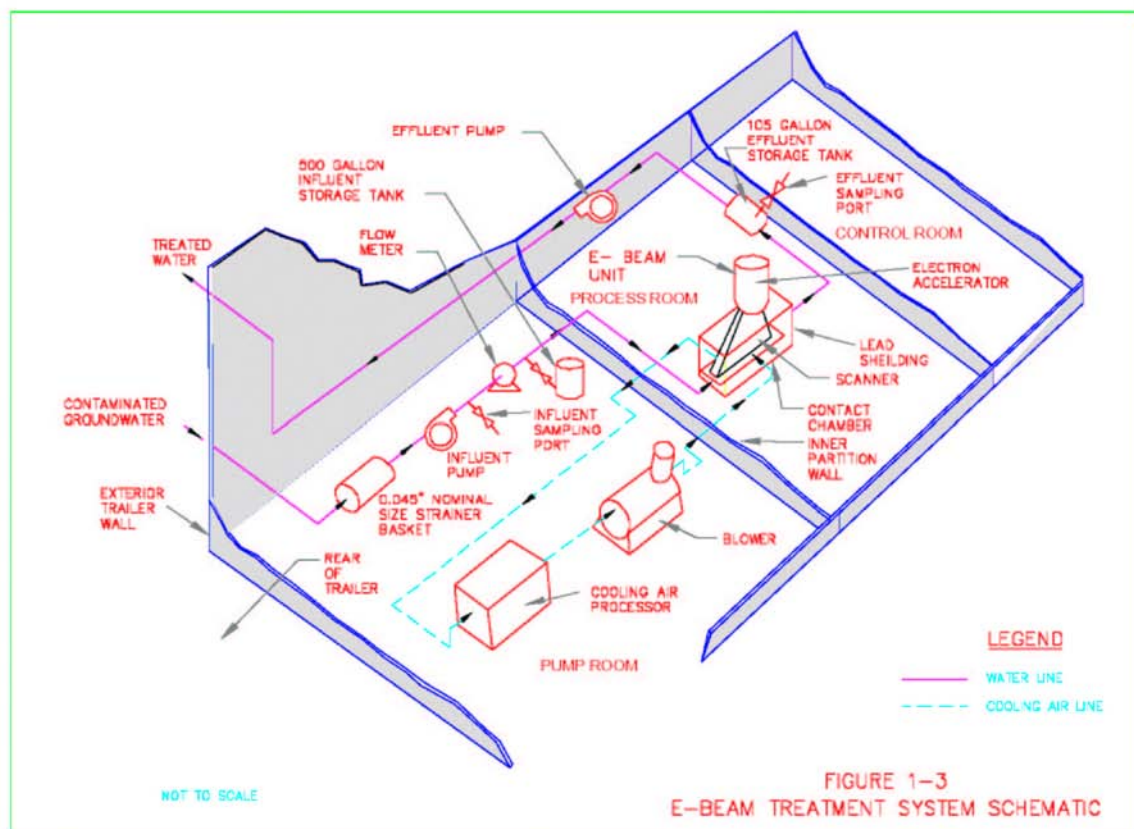
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2   TREATMENT EFFECTIVENESS

This section presents the results of the demonstration of the E-Beam technology at the NBVC in Port Hueneme, California and describes the effectiveness of the technology in treating groundwater contaminated with MtBE and other gasoline components. The E-Beam technology demonstration was conducted at the Source Zone within the MtBE plume at the NBVC during the Summer and Fall of 2001.

The demonstration at the NBVC was guided by the technical representatives of a group of stakeholders that included the following organizations:

- U.S. EPA, National Risk Management Research Laboratory (NRMRL)
- U.S. Navy, Naval Facilities Engineering Service Center (NFESC)
- U.S. EPA, Region 9
- California Department of Health Services (DHS)

Each of these stakeholders participated in conference calls and meetings at the site to discuss the technical details of the demonstration and to ensure that the technical approach to the demonstration adequately addressed elements of interest to potential users of the E-Beam

technology. NFESC and NRMRL worked cooperatively to staff the field sampling crews and to manage the evaluation.

2.1   Background

To characterize the contaminated groundwater at the demonstration location within the Source Zone, seven temporary wells were installed just east of Harris Street in the area of the Extraction Zone. The wells, designated T-1 through T-7, were installed in a line trending north to south with well 1 being the farthest north and well 7 the farthest south. Subsequently, to feed contaminated groundwater to the treatment system, these temporary wells were replaced with a series of five extraction wells, designated S-1 through S-5, as shown in Figure 1-2.

Hydrogeological modeling by NRMRL indicated that the maximum available flow rate from the five extraction wells would be 7 gpm. The E-Beam system was designed for a continuous flow rate of 40 gpm, and Haley and Aldrich indicated that flows lower than about 10 gpm result in some operational difficulties. Therefore, Haley and Aldrich made some refinements to the E-Beam dosing chamber in order to accommodate lower flows and it was planned that the demonstration would be conducted at the maximum available flow rate of 7 gpm.

Groundwater at the Source Zone was known to be contaminated with gasoline components. The primary components of environmental concern included BTEX, MtBE, and products of MtBE degradation, including primarily *t*-butyl alcohol (tBA). To confirm the presence of these components and their approximate concentrations in the area, groundwater samples were collected from the seven temporary wells (T-1 through T-7) in September 2000 and then from the five extraction wells (S-1 through S-5) in March 2001. The results of the laboratory analysis of these groundwater samples are shown in Table 2-1 and confirmed the presence of the expected gasoline components.

In addition to the gasoline components identified above, the stakeholders identified a number of potential by-products of chemical oxidation that may well be formed during treatment of the groundwater using the E-Beam technology. Specifically, by-products from the oxidation of MtBE and BTEX were expected to include acetone, aldehydes, and glyoxals. In addition, bromate formation might result from oxidation of the bromide. Finally, the potential reuse of the effluent as a drinking water supply resulted in the identification of several by-products of subsequent chlorination treatment as constituents of interest. These constituents included total trihalomethanes (TTHM), haloacetic acid (HAAs), and N-nitrosodimethylamine (NDMA).

The contaminants of interest identified above were therefore included on the list of analytical variables to be determined in both influent and effluent samples during the demonstration to assess the effectiveness of E-Beam treatment. Based on a review of regulatory criteria for these contaminants of interest and discussions among the stakeholders, effluent treatment goals were established for selected contaminants of interest as listed in Table 2-2. The treatment goals for MtBE, BTEX and tBA were identified as the lowest maximum contaminant level (MCL) or action level (AL) promulgated by the State of California. For TTHMs and HAAs, the treatment goal was based on the anticipated requirements of the Stage 2 Disinfection By-product Rule (DBPR). These requirements have been proposed in a Notice of Agreement in Principle dated December 20, 2000 (65 FR 251, pages 83015-83024). The other regulatory

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criteria presented in Table 2-2 for critical and non-critical variables were used as advisory information and not as a basis for setting the treatment goals for this demonstration.

Table 2-1. Summary of Site Characterization Analytical Results for the Source Zone							
Well No.	Sample ID	MtBE, µg/L	tBA, µg/L	Benzene, µg/L	Toluene, µg/L	Ethylbenzene, µg/L	Xylenes, µg/L
Initial Characterization Sampling Event, September, 2000							
T-1	920	930	NA	400	660	280	1,100
T-2	945	2,600	NA	840	1,100	460	1,600
T-3	1,010	2,200	NA	730*	590	280	950
T-4	1,045	25	NA	233*	110	<1.0	530*
T-5	1,115	6	NA	22	110	370*	870*
T-6	1,530	8	NA	4	17	12	44
T-7	1,555	140	NA	5	26	31	86
Additional Characterization Sampling Event, March 13-14, 2001							
S-1	1,406	569	59	118	<1	7	1,130
S-2	1,440	233	17	0	0	0	3
S-3	1,504	1,400	197	623	276	1,230	1500
S-4	1,535	2,160	270	1,030	<1	470	1500
S-5	1,600	5,100	510	3,170	802	1,740	4030

*estimated results
NA = not analyzed

Table 2-2. Development of Treatment Goals for the MtBE Technology Demonstration Program based on Applicable Regulatory Criteria

Contaminant		CA Primary MCL[a], μg/L	CA Secondary MCL[a], μg/L	CA Action Level[a], μg/L	CA Public Health Goal[a], μg/L	Stage 2 DBPR MCL[b], μg/L	Demonstration Treatment Goal, μg/L
VOCs	MtBE*	13	5	NA	13	NA	5
	tBA*	NA	NA	12	NA	NA	12
	Acetone*	NA	NA	NA	NA	NA	NA
	Benzene*	1	NA	NA	0.14[b]	NA	1
	Toluene*	150	NA	NA	150	NA	150
	Ethylbenzene*	700	NA	NA	300	NA	700
	Xylenes[c]*	1,750	NA	NA	1,800	NA	1,750
DW Variables (SDS Testing)	TTHMs	100	NA	NA	NA	80	80
	HAAs	NA	NA	NA	NA	60	60
	NDMA	NA	NA	0.02	NA	NA	0.02
Aldehydes & Glyoxals	Formaldehyde	NA	NA	NA	NA	NA	NA
	Acetaldehyde	NA	NA	NA	NA	NA	NA
	Heptaldehyde	NA	NA	NA	NA	NA	NA
	Glyoxal	NA	NA	NA	NA	NA	NA
	Me-Glyoxal	NA	NA	NA	NA	NA	NA
Wet Chemistry	Bromate	NA	NA	NA		10	10

Abbreviations:

CA: State of California

DBPR: Disinfection Byproduct Rule

DO: Dissolved Oxygen

DW: Drinking Water

EPA: U.S. Environmental Protection Agency

HAAs: Haloacetic Acids

MtBE: Methyl-t-Butyl Ether

NA: Not available

SDS: Simulated Distribution System

tBA: t-Butyl Alcohol

TBD: To be determined

TOC: Total organic carbon

TTHMs: Total trihalomethanes

VOCs: Volatile organic compounds

Notes:

*: Critical contaminant associated with a primary demonstration objective

a) Sources: California DHS Primary MCLs and Lead and Copper Action Levels (January 2001), Secondary MCLs (May 2000), Action Levels (February 2001), Public Health Goals (January 2001)

b) Draft or proposed values

c) Single isomer or sum of isomers

The demonstration of the E-Beam technology was implemented in two phases. In the first phase, the technology was evaluated during over a two-week period during July 2001 at essentially steady-state operating conditions. For this main phase of the demonstration, a specific set of objectives was formulated and a technology evaluation plan/quality assurance project plan (TEP/QAPP) was written to guide the field sampling, laboratory analysis, and data evaluation efforts. In the second phase, the E-Beam dose was varied in a series of short runs during one week in November, 2001. The purpose of this second phase was to determine the optimum dose for minimizing by-products while still maintaining adequate destruction of the primary contaminants of interest (MtBE and BTEX).

2.2   Demonstration Approach: Phase I

The following sections describe the demonstration objectives and sampling design for Phase 1 of the demonstration, the technology operations during this phase, and the sampling and analytical procedures.

2.2.1   Demonstration Objectives and Sampling Design

One primary objective and six secondary objectives were identified for the main phase of the demonstration. The primary objective and the measurement needed to fulfill this objective were considered critical for the technology evaluation; secondary objectives were related to additional information that was useful but not critical.

2.2.1.1   Primary Objective

The primary objective was to evaluate whether the E-Beam technology will reduce the MtBE, tBA, and BTEX levels to less than the treatment goals established for the demonstration program. To fulfill this primary objective, grab samples of influent and effluent groundwater were collected three times each weekday for a 2-week period. Each of these samples was analyzed for a list of VOCs that included MtBE, tBA, and BTEX.

2.2.1.2   Secondary Objectives

The secondary objectives for this demonstration were the following:

1.   Monitor for formation of reaction by-products (i.e., acetone, aldehydes, and glyoxals).

2.   Determine whether the effluent meets the TTHM and HAAs requirements of the Stage 2 DBPR when subjected to Uniform Formation Conditions (UFC).

3.   Use a chloramine UFC test to assess potential for formation of NDMA.

4.   Monitor certain water quality variables, including pH, temperature, dissolved oxygen (DO), chemical oxygen demand (COD), and dissolved and total organic carbon (DOC/TOC), as well as the flow rate.

5.   Define operating costs (power/energy consumption, chemical costs) over a set period of stable operation.

6. Determine if the technology results in a significant increase in the bromate concentration in the effluent as compared to the influent.

To fulfill Secondary Objectives 1, 4, and 6, grab samples of the influent and effluent groundwater were collected once each weekday and analyzed for the listed variables. To fulfill Secondary Objectives 2 and 3, grab samples of the effluent were collected two times during the demonstration and shipped to the NRMRL drinking water laboratory, where the samples were subjected to chlorination according to Simulated Disinfection System (SDS) testing protocols.

2.2.2 Technology Operations

The pump and hosing that was already present in the pump room of the E-Beam process trailer was used to extract groundwater from the five extraction wells into the E-Beam treatment system. The flow from the wells was fed directly into the treatment system, bypassing the influent tank, and the effluent was discharged to the NBVC sanitary sewer system under an appropriate permit. To determine the hydraulic residence time of the treatment system, a tracer study was conducted following startup of the E-Beam system but prior to initiation of the treatment runs. Sodium chloride was added to the influent and the effluent was monitored with a conductivity meter to determine the mean residence time. The test was repeated four times at the planned flow rate of 7.0 gpm; the mean hydraulic residence time was calculated to be 2 minutes and 45 seconds.

During Phase 1, the E-Beam system was operated at a power input corresponding to a radiation dose of 1,200 krads, which Haley and Aldrich indicated would be adequate to destroy MtBE at the concentrations historically observed at this location. The E-Beam treatment system was operated only during the day, from approximately 7 a.m. to 6 p.m., and was shut down at night at the request of the NBVC for security and safety reasons. Each morning during the demonstration period, the system was started up by the E-Beam operator and allowed to run for approximately 1 hour to ensure that the process was at a steady operational state before any sampling was conducted.

2.2.3 Sampling and Analytical Procedures

During the demonstration, grab samples of the groundwater were collected before and after treatment at the E-Beam influent and effluent sampling locations. Sampling was conducted between the hours of 8 a.m. and 6 p.m. each day. Three grab samples were collected for volatile organic compound (VOC) analysis at about 4-hour intervals on each of the 10 sampling days to generate a total of 30 samples for VOCs. One grab sample was collected each sampling day for analysis of aldehydes/glyoxals and general water quality characteristics to generate a total of 10 samples for each of these variables.

All samples were collected directly into sample jars from the valved taps in the E-Beam system influent and effluent lines. Prior to sample collection, the valved water taps were purged briefly to ensure that any stagnant water had been flushed out of the tap. A description of the sample container and preservative utilized for each type of sample is provided in Table 2-3. Each water sample for VOC analysis was collected in three 40-mL volatile organic analysis (VOA) vials containing hydrochloric acid to acidify the sample to a pH < 2. The water sample was gently introduced into the sample containers to reduce agitation and loss of volatile compounds.

Each vial was filled until a meniscus appeared over the top of the vial. The screw-top lid with the septum (Teflon side toward the sample) was then tightened onto the vial. After the lid was tightened, the vial was inverted and tapped to check for air bubbles. If any air bubbles were present, the sample was recollected. For all other analytes, water was introduced directly into the appropriate container, as listed in Table 2-3, and the lid was tightened immediately after filling. Field duplicates and other quality control (QC) samples were collected immediately following collection of the original sample. After collection, each water sample was stored on ice in a cooler until readied for shipment to the analytical laboratory. All sample collection procedures were in accordance with the reference method listed in Table 2-3.

To evaluate the potential formation of by-products after treatment with the electron beam process, it was determined that the SDS testing protocol, which was established under the DBPR and simulates the effects of chlorination under UFC, would be used. A bulk 1-gallon effluent water sample, before and after treatment, was collected two times during the demonstration and sent to NRMRL for SDS testing and subsequent analysis of chlorination by-products.

Following sample collection, each sample was labeled with detailed information regarding the location, date, and time of collection. Chain-of-custody procedures were followed from sample collection through sample analysis.

Each effluent grab sample was taken approximately one hydraulic retention time following the collection of the corresponding influent sample to ensure that the same parcel of water was being sampled before and after treatment. Since the flow rate was maintained at 7.0 gpm throughout the demonstration, effluent samples were taken about 2 minutes and 45 seconds following collection of the influent sample during each sampling event.

Field variables that were measured on influent and effluent water included pH, temperature, and DO. These measurements were taken using a Horiba U-22 water quality meter on a separate grab sample in conjunction with each influent/effluent sampling event. Laboratory measurements that were conducted are listed in Table 2-3. All laboratory measurements were conducted in accordance with the EPA reference method.

2.3   DEMONSTRATION APPROACH: PHASE 2

During Phase 2, the E-Beam system was operated at three different power inputs, corresponding to radiation doses of 800, 1,200, and 1,600 krads. The flow rate and other operating conditions for Phase 2 were the same as for Phase 1. Because influent groundwater was pumped directly from the extraction wells, and these wells had only recently been installed, there was some concern that the influent groundwater might contain atypically high levels of suspended matter. To assess whether this suspended matter might have any influence on the performance of the treatment system, a replicate run was conducted at each of the three power levels wherein a 1-micron cartridge filter was inserted into the influent line to filter out suspended matter prior to treatment. The sampling and analytical procedures for Phase 2 of the demonstration were identical to Phase 1.

2.4   RESULTS FOR PHASE 1

All planned measurements were taken, and no outliers were identified. Thus, 100% completeness was achieved for field variables. The results are summarized below:

- The flow rate ranged from 6.8 to 7.0 gpm, and averaged 6.97 gpm.
- The pH averaged 6.80 in the influent and 7.01 in the effluent.
- The dissolved oxygen content of the groundwater increased from 5.70 mg/L in the influent to 7.32 mg/L in the effluent.
- The temperature of the influent averaged 23.9° C; the effluent temperature averaged about 26.2°C (2.3° C higher).

Table 2-3. Analytical Variables and Method Requirements

Analytical Variable	Target Analytes	Method Reference	Container	Holding Time	Preservation	Analytical Laboratory
Volatile organics	MtBE	SW-846 5030B/8260B	3 x 40 mL amber glass vial	1-4 days (anal.)	HCl to pH<2	ALSI
	tBA					
	BTEX					
	Acetone					
Aldehydes/Glyoxals	Formaldehyde	MDOCDW 556 Mod.	2 x 50 mL amber glass	7 days(ext)/ 14 days (anal)	25 mg $CuSO_4.5H_2O$	MW
	Acetaldehyde					
	Methyl glyoxal					
	Glyoxal					
	Heptaldehyde					
General Chemistry	TOC	MCAWW 415.1	1 x 250 amber glass	28 days	HCl to pH<2	ALSI
	DOC	MCAWW 415.1 Mod.				
	COD	MCAWW 410.4			H_2SO_4 to pH<2	
	Bromide ion	MCAWW 300.0	1 x 500 mL polyethylene		None	
	Bromate ion	MCAWW 317	1 x 50 mL amber glass		5 mg EDA	MW
Bulk SDS Test Sample	NA	SDS UFC Test	6 x 1 L amber glass	Not specified	None	
Disinfection Byproducts (in SDS Effluent)	TTHMs	MDOCDW 551	2 x 60 mL amber glass	14 days (ext)/ 14 days (anal)	10 mg NH_4Cl	EPA NRMRL
	HAAs	MDOCDW 552.1	2 x 50 mL amber glass	14 days (ext)/ 7 days (anal)		
	NDMA	40 CFR 136, Meth. 1625 Mod.	2 x 1 L amber glass	30 days (ext/ anal)	20 mg ascorbic acid	MW

Abbreviations:
ALSI: Analytical Laboratory Services, Inc
Anal: Analysis
CFR: Code of Federal Regulations
COD: Chemical Oxygen Demand
CuSO4.5H2O: Copper sulfate pentahydrate
DOC: Dissolved Organic Carbon
EDA: Ethylane diamine
Ext.: extraction
HAAs: Haloacetic acids
MCAWW: Methods for the Chemical Analysis of Water and Wastes (EPA 1998a)
MDOCODW: Methods for determination of organic compounds in drinking water
MW: Montgomery Watson Laboratories
NDMA: N-nitrosodimethylamine
NRMRL: National Risk Management Research Laboratory
SDS: Simulated Distribution System
SW-846: Test Methods for the Evaluation of Solid Wastes (EPA 1996)
TOC: Total organic carbon
TFE: tetrafluoroethene
TTHMs: total trihalomethanes
UFC: Uniform Formation Conditions

The increase in effluent temperature was consistent with the process chemistry for the E-Beam technology, as discussed in Section 1.3.1. A 100% completeness was achieved for laboratory variables with the exception of NDMA. Other analytical tests consumed the entire available SDS effluent sample; therefore, insufficient sample was available to the laboratory for NDMA analysis.

2.4.1   Trends in Results for Critical VOCs

The laboratory analytical results for each critical VOC variable are plotted in Figure 2-1 and 2-2. In each of these plots, the date of sampling is shown on the x-axis, and the concentrations of the critical variables are shown on the y-axis.

Figure 2-1 shows the influent and effluent MtBE (upper panel) and tBA (lower panel) concentrations during the two-week demonstration period. Each day, 3 replicate samples were collected, one in the morning, one around noon to mid-afternoon, and one in late afternoon. The effluent samples were temporally related to the influent samples. Since the scale of the figure is logarithmic, the increase in influent MtBE concentration from 1,400 to 2,000 over the time period is not clearly noticeable. This increasing trend in influent MtBE concentration may have resulted from the drawing in of higher concentration regions of the plume into the extraction wells. Effluent MtBE concentrations were always less than the treatment goal of 5 μg/L established at the beginning of the project (dotted horizontal line in the figure), and variability was low.

The lower panel of Figure 2-1 summarizes the influent and effluent tBA concentrations. The dotted horizontal line signifies the treatment goal of 12 μg/L, which was the compliance target established in the project objectives. tBA was never in compliance with that treatment goal for the duration of the demonstration period at the dose rate studied. The rate constant for the reaction of hydroxyl radical with tBA is 6.0×10^8 M^{-1}s^{-1}, or about half that of MtBE. Therefore, even though MtBE removal was consistently effective, tBA removal was consistently less so. This is because of the competition for high energy electrons and oxidative radicals by the other organic constituents in the influent groundwater as well as the lower rate constant for oxidation of tBA as compared to other organic constituents.

Figure 2-2 (a-d) summarizes the behavior of the BTEX compounds in the groundwater during the 2-week demonstration period. Again, the dotted lines in the figure panels represent the treatment goals for the respective compounds. Benzene and toluene were both consistently reduced by 3 orders of magnitude to below their respective treatment goals. Ethylbenzene and xylenes were already below their treatment goals in the influent, and they were reduced further to below detection limits by exposure to the electron beam (the laboratory quantitation limit was 0.5 μg/L for ethylbenzene and 1.5 μg/L for total xylenes).

Figure 2-1. MtBE and tBA Influent and Effluent Concentrations over the Phase 1 Demonstration Period
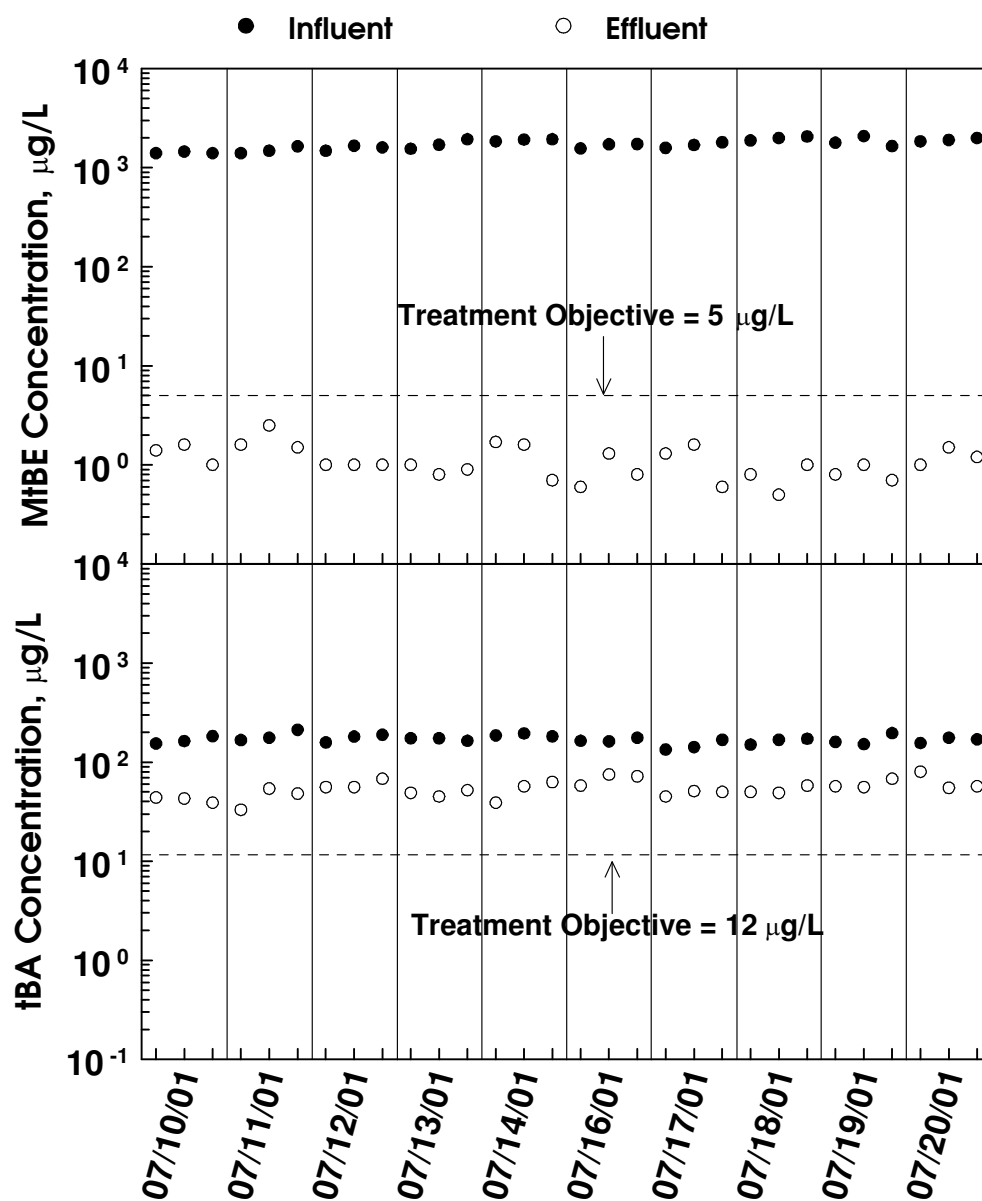
Figure 2-2. BTEX Influent and Effluent Concentrations over the Phase 1 Demonstration Period
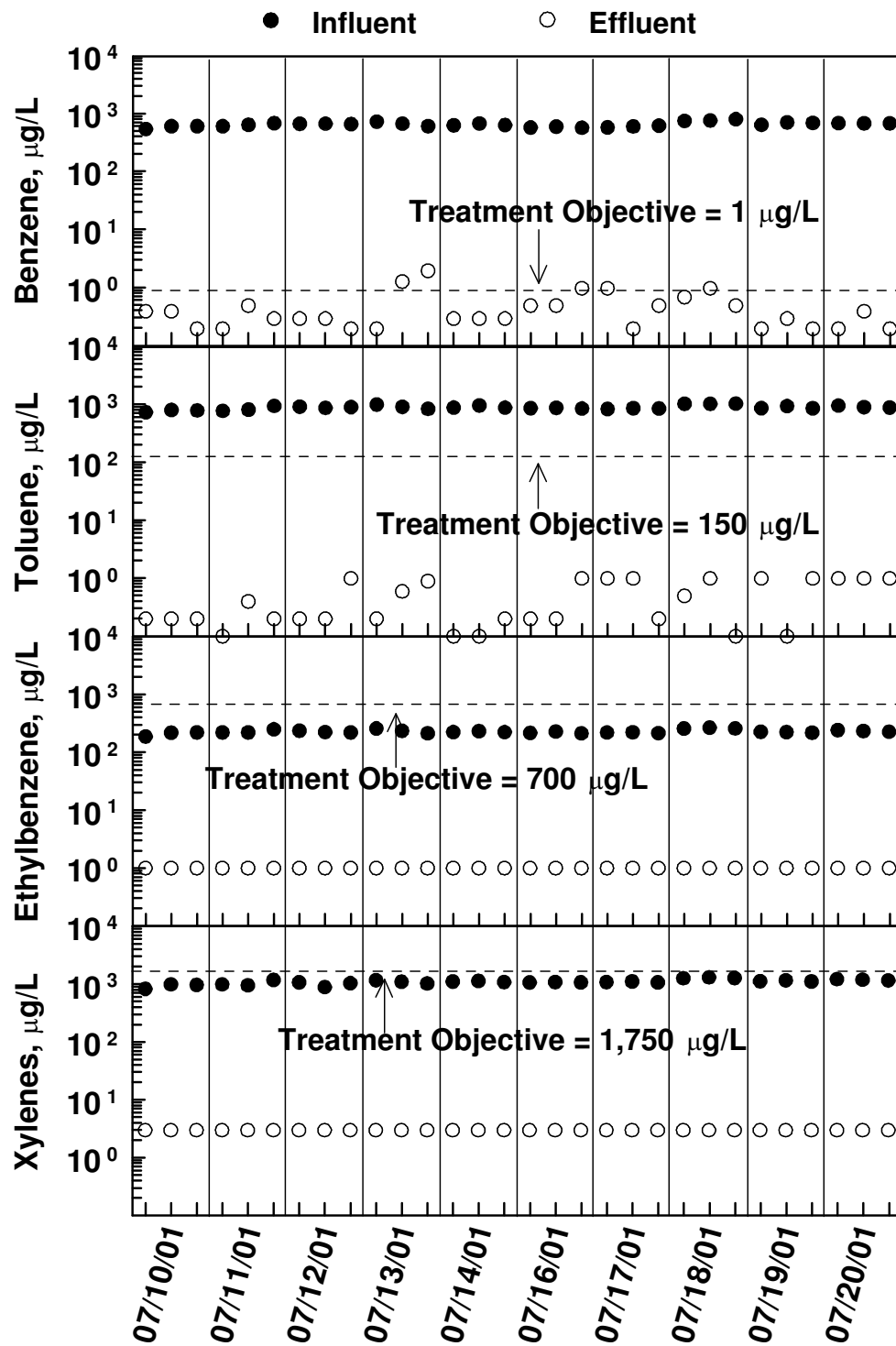
2.4.2   Statistical Analysis of Results

In accordance with the TEP/QAPP, a preliminary statistical evaluation of the laboratory analytical results for each measured target analyte was conducted. Descriptive summary statistics were calculated for each contaminant of interest in the influent and effluent groundwater. To calculate these statistics, non-detections were replaced with a simple substitution of one-half the laboratory quantitation limit. Statistical plots were generated to graphically describe the concentrations of these contaminants in the sample populations of influent and effluent water.

Normal probability plots depicting the data for MtBE, tBA, and BTEX showed a reasonable fit to a theoretical normal distribution for most of these variables. Two contaminants (ethylbenzene and xylenes) were not detected in any effluent samples, so statistical tests were not applicable. For each of the other four variables, a normal distribution was assumed and the one-sample, one-tailed t-distribution was used to calculate 95 percent confidence limits and to perform statistical comparisons to the treatment goal.

The critical contaminants that were established to be tested for compliance with treatment goals in the project objectives included MtBE, tBA, and BTEX. Table 2-4 lists the mean and the 95 percent upper confidence limit (UCL) of the mean influent and effluent concentrations of these contaminants, as well as the overall removal efficiency. Figures 2-3 and 2-4 compare the mean influent and daily UCL for the effluent concentrations of these contaminants to the treatment goals. As shown in Figure 2-3, the daily effluent UCL for MtBE was consistently below the 5-µg/L treatment goal. However, for tBA, the daily effluent UCL was significantly above the 12 µg/L treatment goal. In all cases except tBA and one point for benzene, the effluent concentrations of these critical contaminants were in compliance with project objectives. As stated in Section 2.4.1, the rate constant for reaction of hydroxyl radicals with tBA is about half that for MtBE. Thus, the presence of other organic compounds in the groundwater competing for the hydroxyl radicals and aqueous electrons would have a greater influence on tBA destruction than MtBE.

Table 2-5 and Figure 2-5 present the performance of the electron beam in regards to its effect on the measured oxidation by-products (acetone, formaldehyde, glyoxal, and bromate ion). Table 2-5 lists the mean and the overall 95 percent upper confidence limit (UCL) of the mean influent and effluent concentrations of these contaminants. Figure 2-5 compares the daily influent and effluent concentrations of these contaminants over the time period of Phase 1 of the demonstration. All of the organic by-products increased substantially in concentration from the influent to the effluent as a result of chemical oxidation reactions. Acetone and formaldehyde were the two most prevalent organic by-products, which is consistent with results of previous studies of chemical oxidation processes in similar applications. Bromate ion did not increase in concentration from the influent to the effluent and was present only at concentrations near the laboratory quantitation limit (1.0 µg/L) in both these streams.

Table 2-4. Mean, 95 Percent UCL, and Removal Efficiency for MtBE, tBA, and BTEX

Compound	Influent		Effluent		Removal Efficiency
	Mean Concentration, µg/L	UCL, µg/L	Mean Concentration, µg/L [1]	UCL, µg/L [1]	
MtBE	1721	1784.5	1.1	1.2	99.94%
tBA	170	175.3	54.2	57.6	68.14%
Benzene	664	683.1	0.4	0.6	99.94%
Toluene	890	913.3	0.3	0.4	99.97%
Ethylbenzene	220	233.5	ND(0.5)	NA	>99.77%
Total Xylenes	1090	1123.7	ND(1.5)	NA	>99.86%

[1] Where less than 20 percent non-detects were present in the sample population, the mean concentration and UCL were determined by setting non-detect results equal to one-half the laboratory quantitation limit.

NA = Not applicable; a UCL could not be calculated because most results were non-detects.

ND = Not detected in any of the effluent samples.

UCL = 95 percent upper confidence limit for the mean

Table 2-5. Concentrations of By-products in Influent and Effluent Water

Compound	Influent		Effluent	
	Mean Concentration, µg/L[1]	UCL, µg/L[1, 2]	Mean Concentration, µg/L	UCL, µg/L[2]
Acetone	6.9	8.8	160	165.0
Acetaldehyde	1.1	1.3	14.7	15.7
Formaldehyde	6.8	7.3	125.0	136.0
Glyoxal	1.7	2.0	8.8	10.5
M-Glyoxal	1.2	1.5	34.5	37.4
Bromate	1.3	1.6	1.3	1.6

[1] Where non-detects were present in the sample population, the mean concentration and UCL were determined by setting non-detect results equal to one-half the laboratory quantitation limit.

[2] The UCL listed reflects a one-sided 95 percent probability upper limit for the population mean using a t-test.

UCL = Upper confidence limit

Figure 2-3. Mean Influent and 95 Percent UCL Effluent Concentrations of MtBE and tBA in the Phase I Portion of the Demonstration.
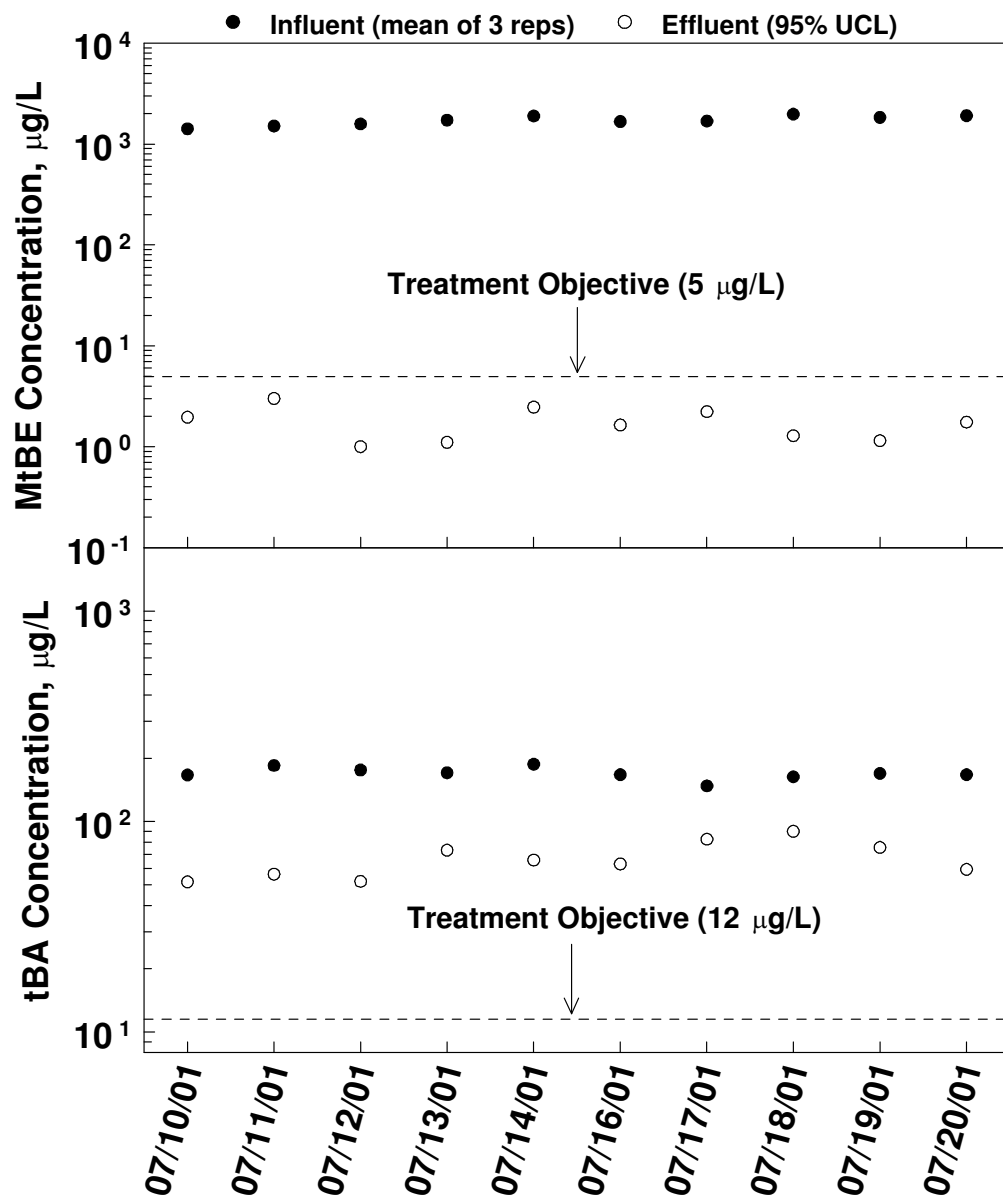
Figure 2-4. Mean Influent and 95 Percent UCL Effluent Concentrations of BTEX in the Phase I Portion of the Demonstration.
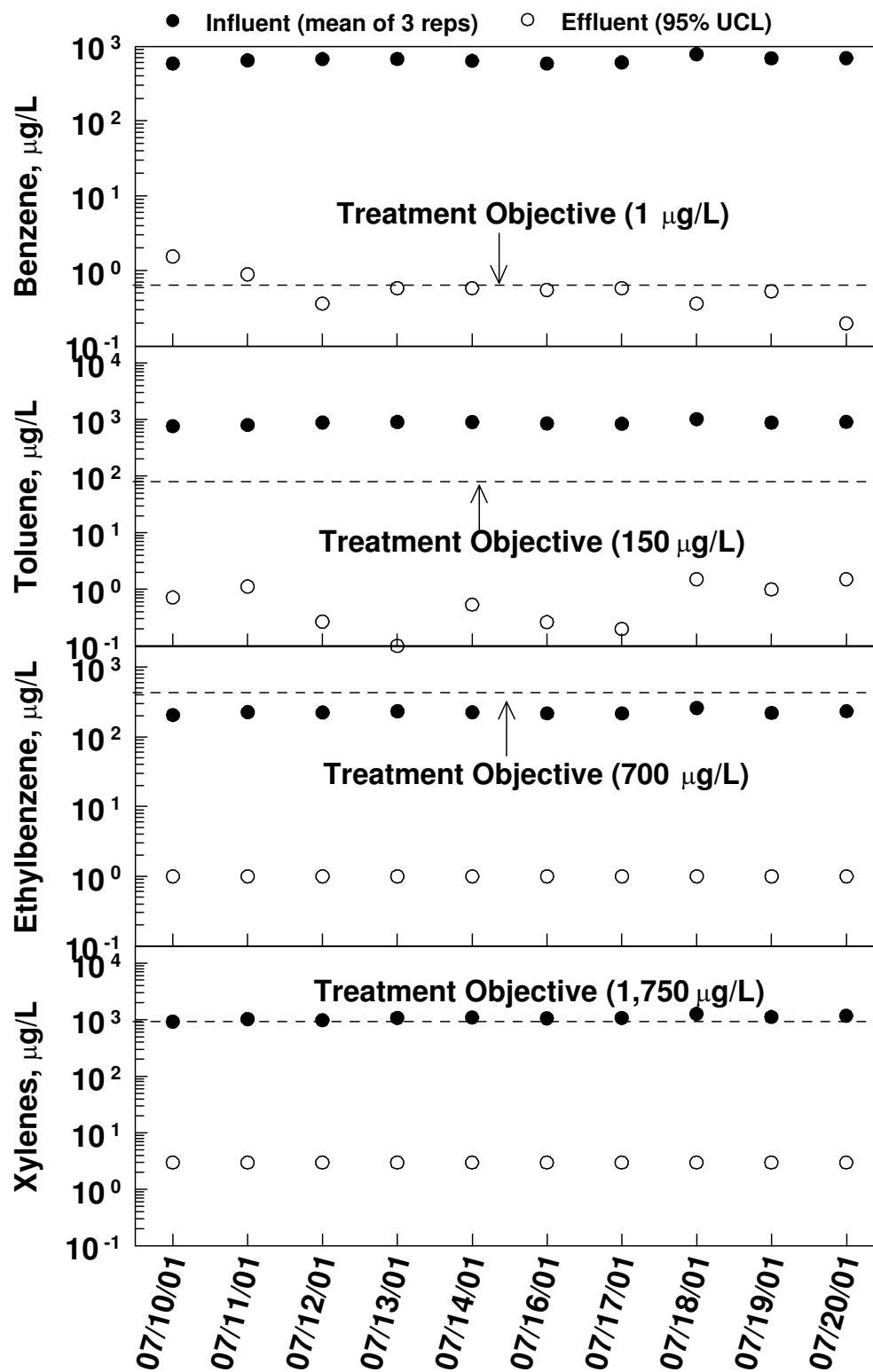
Figure 2-5. Acetone, Formaldehyde, Glyoxal, and Bromate Influent and Effluent Concentrations in the Phase 1 Portion of the Demonstration (the square symbols in the bottom panel represent the fact that the bromate concentrations in the influent and effluent were identical).

25
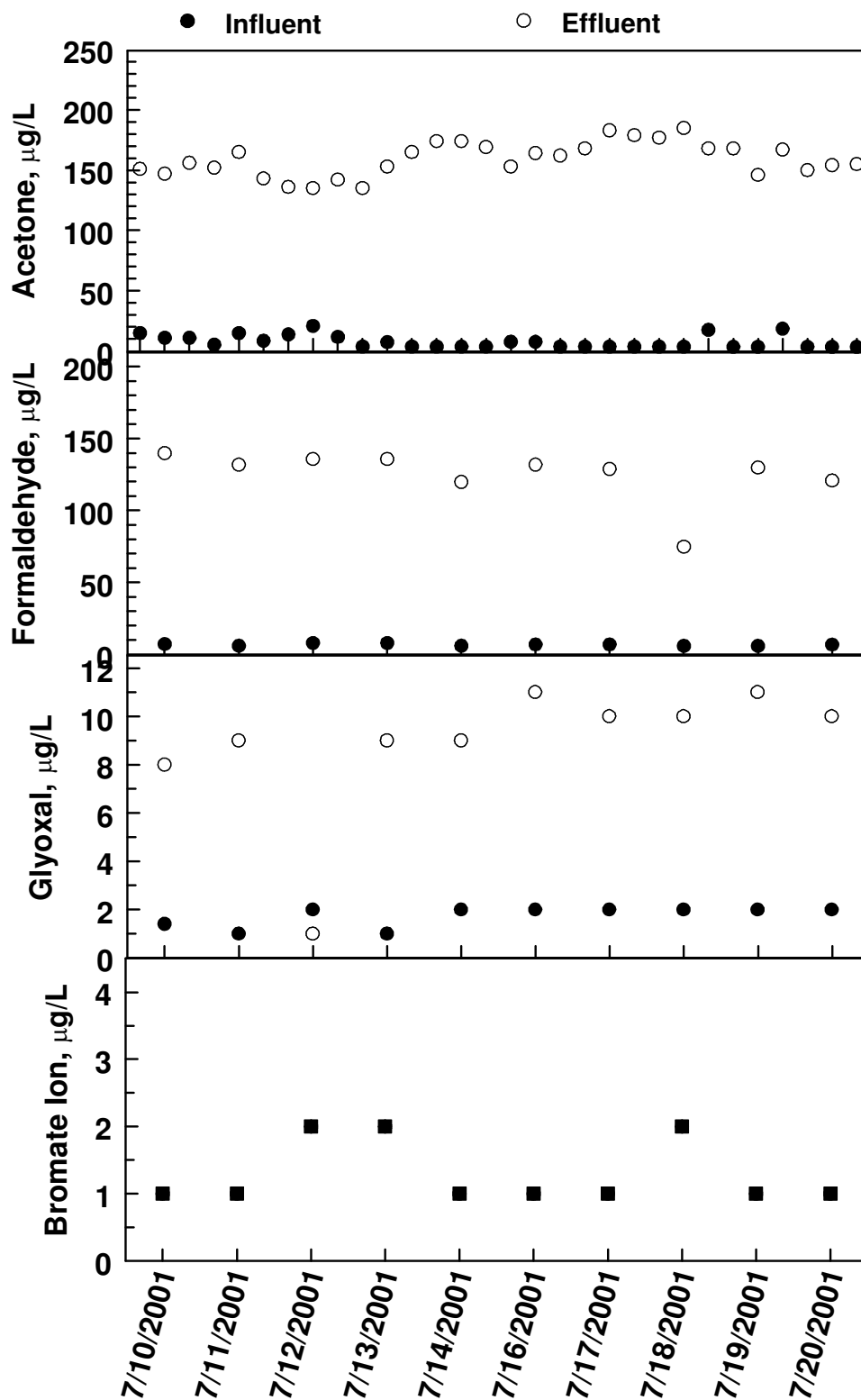
Table 2-6 and Figure 2-6 show the effect of the electron beam on other measured water quality variables (COD, TOC, DOC, and bromide ion). Table 2-6 lists the mean and the UCL for influent and effluent concentrations of these analytical variables. Figure 2-6 compares the daily influent and effluent concentrations of these variables over the time period of Phase 1 of the demonstration. COD concentrations were nearly identical in the influent and effluent streams, but both TOC and DOC increased significantly in concentration from the influent to the effluent. Bromide ion concentration did not change in response to exposure to the E-Beam.

Table 2-6. Concentrations of General Water Quality Variables in Influent and Effluent Water

Compound	Influent		Effluent	
	Mean Concentration mg/L[1]	UCL, mg/L[1, 2]	Mean Concentration mg/L[1]	UCL, mg/L[1, 2]
TOC	5.4	5.5	13.3	13.8
DOC	5.0	5.2	9.1	9.5
COD	27.4	30.6	26.1	28.6
Bromide	0.9	0.9	0.9	1.0

[1] Where non-detects were present in the sample population, the mean concentration and UCL were determined by setting non-detect results equal to one-half the laboratory quantitation limit.

[2] The UCL listed reflects a one-sided 95 percent probability upper limit for the population mean using a t-test.

UCL = Upper confidence limit

Figure 2-6. COD, TOC/DOC, and Bromide Ion Influent and Effluent Concentrations Over the Phase 1 Demonstration Period.
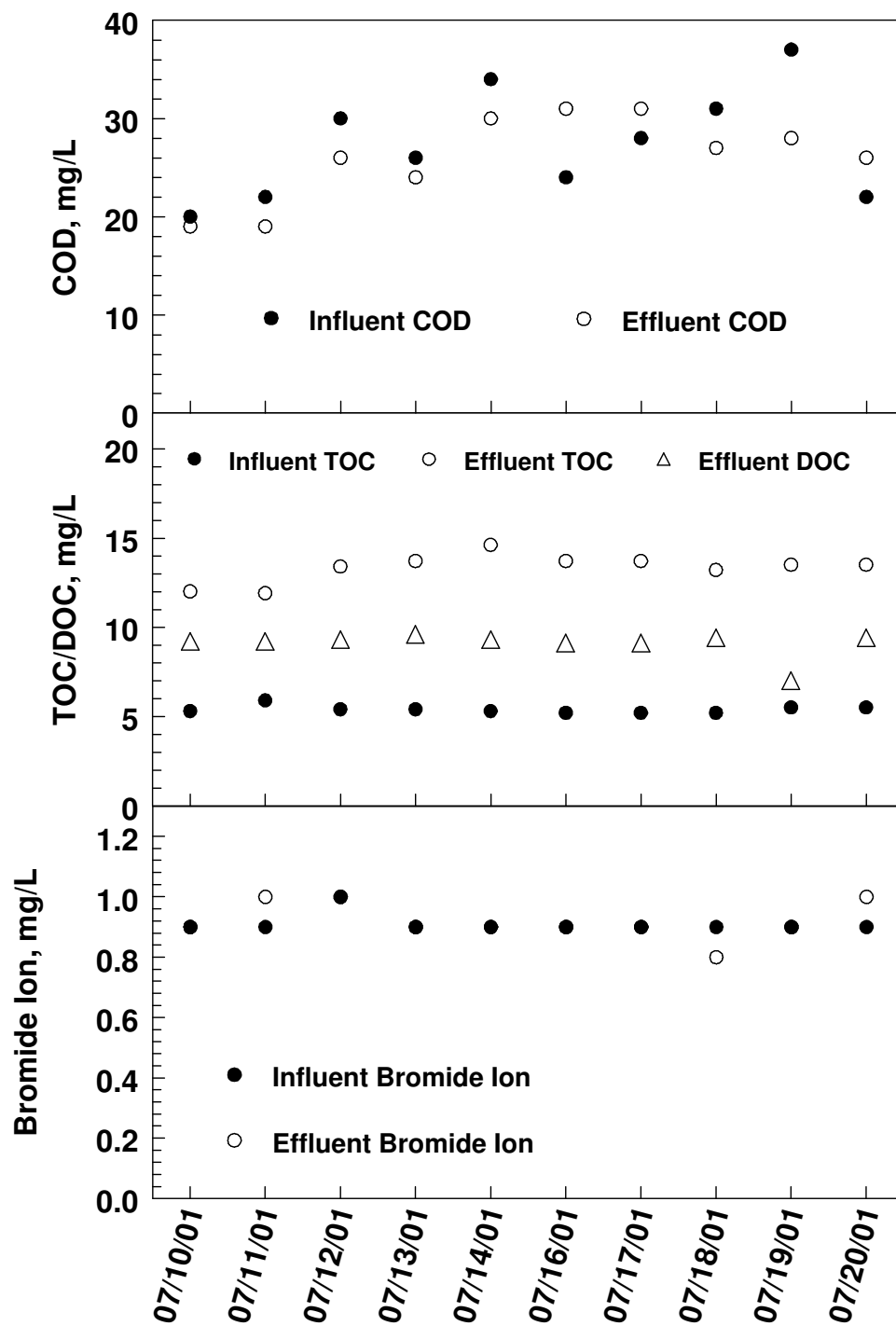
2.4.3. Evaluation of Results Against the Objectives

This section assesses the results of Phase 1 of the E-Beam demonstration in relation to the stated primary and secondary objectives.

Primary Objective: Does the technology reduce the final levels of MtBE, tBA, and BTEX to less than the treatment goals established for the demonstration program? The primary objective was addressed by comparing the UCL for the effluent concentrations of MtBE, tBA, and BTEX to the treatment goals. As described previously, the UCLs were calculated at the 95% confidence level for the means using the one-tailed t-distribution. The overall average UCL for the mean concentrations of MtBE (1.2 μg/L), benzene (0.6 μg/L), and toluene (0.4 μg/L) in the effluent were below the corresponding treatment goals of 5 μg/L, 1 μg/L, and 150 μg/L, respectively. As a result, it was concluded that the primary objective was met for these compounds. The UCL for the mean concentration of ethylbenzene and of total xylenes in the effluent water could not be calculated because all concentrations for these contaminants were below the laboratory quantitation limit. However, the laboratory quantitation limit was less than the treatment goal for each variable; therefore, it was concluded that the primary objective was met for these contaminants as well. In fact, the influent concentrations were already less than the treatment goals.

The UCL for the mean concentration of tBA in effluent water was 57.6 μg/L, which was well above the treatment goal of 12 μg/L. Because the treatment goal was not achieved for tBA, the primary objective for tBA was not met.

Secondary Objective No. 1: Monitor for formation of undesirable reaction by-products, such as acetone, aldehydes, and glyoxals. Other studies of the E-Beam technology and of chemical oxidation processes suggest that partially oxidized organic compounds such as acetone, aldehydes, and glyoxals may result from incomplete oxidation of VOCs and may remain in the effluent from the process (EPA, 1997). This finding was confirmed in the results of the E-Beam technology demonstration at the NBVC. As shown in Table 2-5, concentrations of acetone, acetaldehyde, formaldehyde, glyoxal, and methyl glyoxal in effluent samples were many times the concentrations measured in influent samples, indicating that these compounds were formed during the E-Beam treatment.

There did not appear to be any trends in the concentrations of partially oxidized organic by-products over the two-week demonstration period even though influent organic contaminant concentrations did exhibit increasing trends as described previously. Thus, results indicate that by-product formation was not directly related to influent organic contaminant concentrations.

Secondary Objective No. 2: Determine whether the effluent meets the TTHM and HAA requirements of the Stage 2 DBPR when subjected to UFC. To compare the effluent concentrations with the TTHM and HAA requirements of the Stage 2 DBPR, two influent samples and two effluent samples were subjected to SDS testing. These samples were chlorinated according to UFC protocols and analyzed for TTHM and HAAs. The analytical results of these samples indicated that TTHM and HAAs were formed at levels exceeding the Stage 2 DBPR criteria in both the influent and the effluent samples (see Table 2-7). However, concentrations of TTHM and HAAs were significantly elevated in the effluent samples that were

processed, indicating that the E-Beam treatment generated precursors to the formation of TTHMs and HAAs.

One possible source of the TTHMs was the acetone produced from reaction of the hydroxyl radical with MtBE. Hypothetically, assuming one mole of acetone gives rise to one mole of chloroform (the iodoform reaction), then the mean 160 µg/L acetone (2.78 µM) (Table 2-5) would give rise to 321 µg/L of chloroform. Although this does not account for the total increase in TTHM formation, it is one plausible pathway that could partially explain the increase observed.

Secondary Objective No. 3: Use a chloramine UFC test to assess potential for formation of NDMA. As stated above, insufficient sample was available following SDS testing to complete the NDMA analysis. Thus, no results were obtained for NDMA.

Secondary Objective No. 4: Monitor certain water quality variables, including pH, temperature, DO, COD, and DOC and TOC, as well as the flow rate through the system. During the treatment demonstration, the field team measured the flow, pH, temperature, and DO of influent and effluent water at the sampling locations during each of the three daily sampling events. The results of these measurements were summarized in Sections 2.4 and 2.4.2.

Table 2-7. Summary of TTHM and HAA Results

Compound	Influent Concentration, µg/L	Effluent Concentration, µg/L	Stage 2 DBPR MCL, µg/L
TTHM	165.8	841.4	80
	195.6	631.9	
HAAs	168.7	682.6	60
	169.7	628.3	

Secondary Objective No. 5: Define operating costs (energy consumption, chemical costs) over a 2-week period of stable operation. Operating costs are discussed in the economic analysis of the E-Beam technology in Section 3. The economic analysis utilized operating data from previous demonstrations as well as information collected during this demonstration.

Secondary Objective No. 6: Determine if the technology results in a significant increase in the bromate ion concentration in the effluent as compared to the influent. Table 2-5 lists the mean, as well as the 95% UCL of the mean for bromate ion in both the influent and effluent. These results show that the concentration of bromate ion did not increase from the influent to the effluent. This result was not unexpected since the literature has shown that the E-Beam process is effective in reducing bromate ion to bromide ion (Siddiqui et al., 1996a; 1996b).

2.5   RESULTS FOR PHASE 2

All planned measurements were taken, and no outliers were identified. Thus, 100% completeness was achieved for field variables. The results for field variables are summarized below:

- The influent flow rate ranged from 6.8 to 7.3 gpm, and averaged 7.04 gpm, during the two days of the Phase 2 testing

- The pH averaged 7.04 in the influent and 7.07 in the effluent.

- The dissolved oxygen content of the groundwater increased from 4.1 mg/L in the influent to 5.3 mg/L in the effluent.

- The temperature of the influent averaged 22.0°C; the effluent temperature averaged about 2.0°C higher at 24.0°C.

- Turbidity averaged 1.03 NTU in the influent water.

Concentrations of MtBE and tBA in the effluent (both filtered and unfiltered) declined with increasing dose, as shown in Figure 2-7. A dose of 800 krads was not quite sufficient to reduce the concentration of MtBE to below the treatment goal of 5.0 µg/L, but higher doses were effective in meeting this treatment goal. tBA (unfiltered) was not consistently reduced to below the treatment goal of 12 µg/L even at the highest dose (1,600 krads). However, the trend shown in Figure 2-7 indicates that tBA could have been reduced to below the treatment goal of 12 µg/L at a dose of about 2,000 krads.

Results for BTEX compounds (Figure 2-8) consisted largely of non-detects even at the lowest dose (800 krad). Therefore, there was no measurable difference in performance for BTEX compounds in the power range tested.

Figure 2-7. Concentrations of MtBE and tBA in Filtered and Unfiltered Groundwater as a Function of Applied E-Beam Dose.
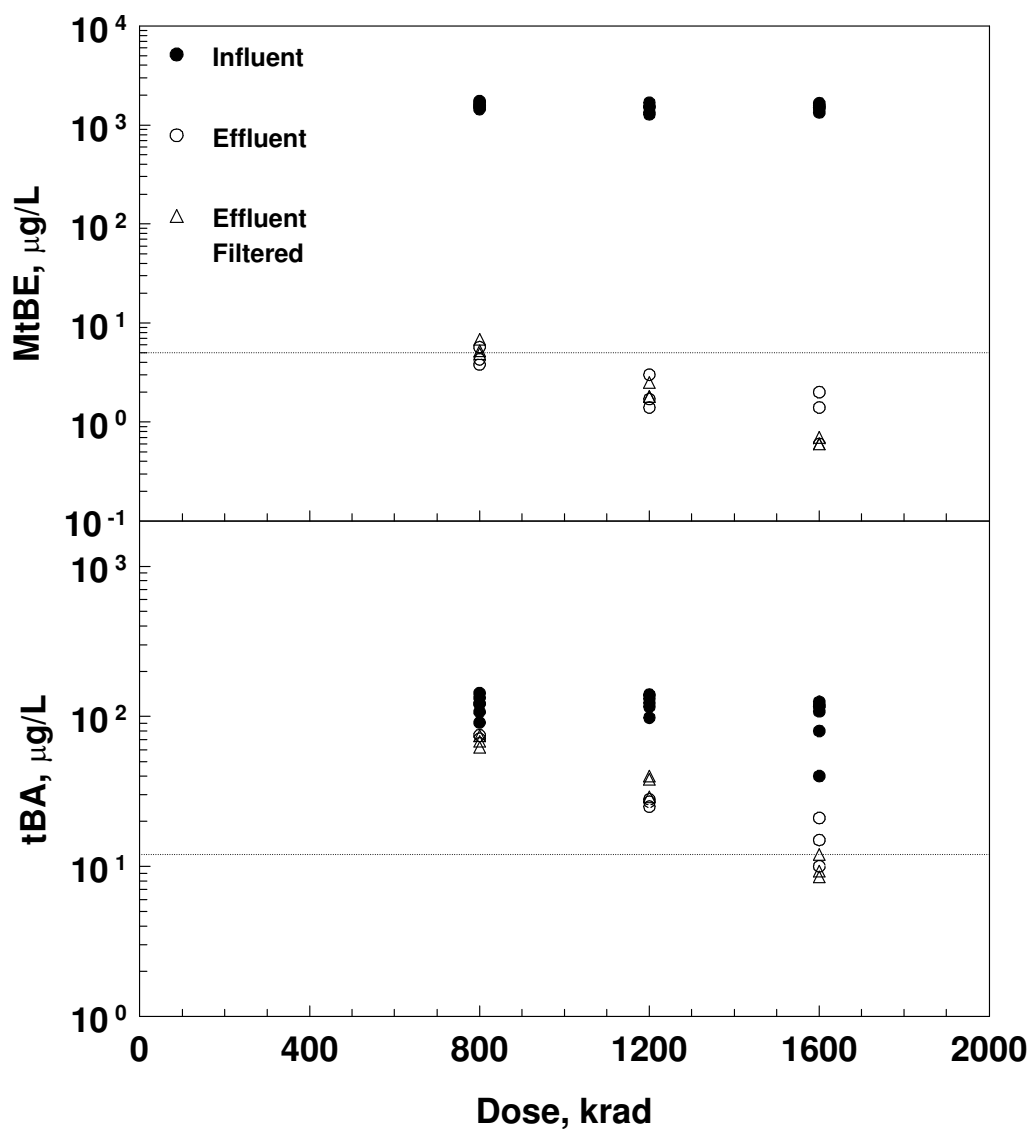
Figure 2-8. Concentrations of BTEX in Filtered and Unfiltered Groundwater as a Function of Applied E-Beam Dose.
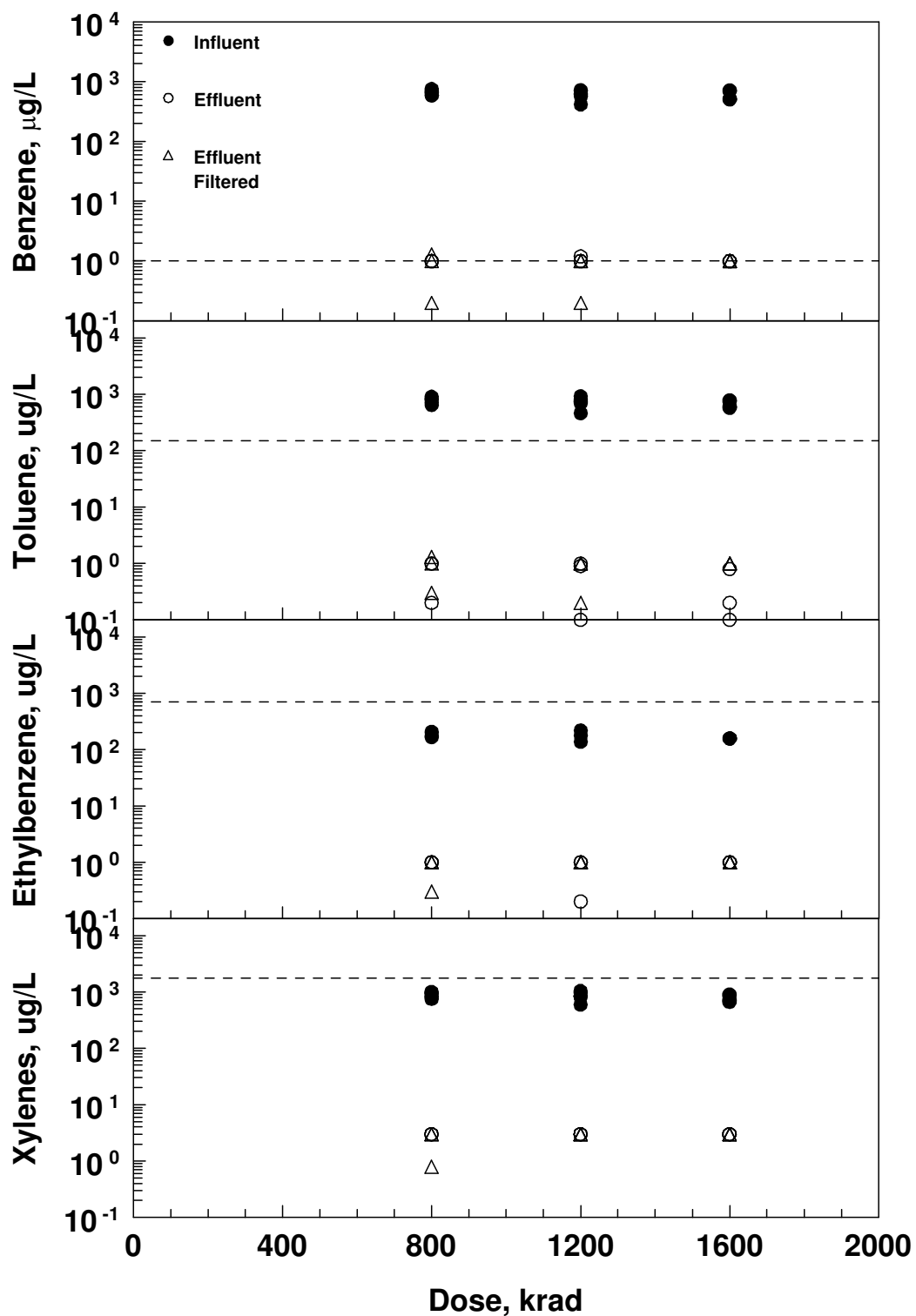
2.6   QUALITY ASSURANCE AND QUALITY CONTROL RESULTS

A data quality review was conducted by Tetra Tech to evaluate the field and laboratory QC results, evaluate the implications of QC data on the overall data quality, document data use limitations for data users, and remove unusable values from the demonstration data sets. The results of this review were used to produce the final data sets to assess the treatment technology and to draw conclusions. The QC data were evaluated with respect to the quality assurance (QA) objectives defined in the project QAPP (Tetra Tech, 2001).

The analytical data for the groundwater samples collected during the E-Beam demonstration were reviewed to ensure that they are scientifically valid, defensible, and comparable. A data quality review was conducted using both field QC samples and laboratory QC samples. The field QC samples included source water blanks, field blanks, trip blanks, matrix spike/matrix spike duplicates (MS/MSD), and sample duplicates. Laboratory QC checks included laboratory blanks, surrogate spikes, and laboratory control sample/laboratory control sample duplicates (LCS/LCSD) (also known as blank spike/blank spike duplicates). Initial and continuing calibration results were also reviewed to ensure the quality of the data and that proper procedures were used. The review focused on assessing the precision, accuracy, completeness, representativeness, and comparability of the data.

All critical variable data were reviewed and at least one sample from each phase of the demonstration was fully validated (recalculated from the raw instrument data). In addition to the above QC checks, reviews of sample chain of custody, holding times, and critical variable identification and quantification were performed.

Overall, the data quality review assessed the critical variable data to be useable for the purpose of evaluating the technology and the attainment of the primary objective for this demonstration. In some instances, results for one or more QC variables were outside of control limits; however, deviations were generally slight, and no broad qualifications of data or other actions were required. A description of the more significant deviations from QC acceptance criteria and the limited impact of these deviations are described below:

- Continuing calibration criteria (percent difference values, or %D) exceeded QAPP criteria for tBA in a few instrument calibration checks during the Phase 2 sampling event. These exceedances were slight, however, and no data were rejected due to calibration problems.

- MtBE was detected at concentrations below 0.4 μg/L in all but one of the method blanks associated with the Phase 2 sampling event. MtBE was detected at similar concentrations in 4 of the 5 trip blanks from this event. Based on laboratory audit findings, these detections are apparently due to the presence of MtBE in the well water used to prepare the blanks. Thus, these blank results were assessed not to indicate a potential high bias in low concentrations of MtBE measured in demonstration effluent samples collected during the Phase 2 sampling event.

- Low concentrations of toluene and other BTEX compounds were detected on an isolated basis in method blanks and trip blanks. As a result, a few low-level results

reported in demonstration effluent samples at less than 5 times associated blank detections were qualified as not detected in the final demonstration data set.

- For the VOC analyses, MS and MSD percent recoveries were generally within the acceptance criteria of 75 to 125% with only a few exceptions, and no data were rendered unusable due to MS/MSD results. In some cases, the percent recoveries for MtBE and other critical variables were above the QC limits in MS/MSDs performed on influent water samples. However, these recoveries were affected by the high native concentrations present in the influent. Therefore, data were not qualified based on the high recoveries. Relative percent differences (RPDs) between the MS and MSD samples were also generally within the acceptance limits.

- For VOCs, LCS/LCSD percent recoveries and RPDs were generally within QAPP acceptance limits. Recoveries of tBA were slightly high and erratic for the Phase 1 sampling event. These observations may indicate a slightly high bias and slightly greater uncertainty associated with the tBA data than for the other critical VOCs. Recoveries of the d_{10}-tBA surrogate in the demonstration samples did not show similar bias or imprecision, however.

- Field duplicates were collected and analyzed at a frequency of 5% or more for the two demonstration sampling events. For the Phase 1 event, field duplicate results uniformly met QAPP precision criteria of ±25% RPD for the critical variables. For the Phase 2 sampling event, RPDs were greater than 25% for tBA in 2 sets of duplicate samples. These samples required dilution due to the presence of other target analytes, however, and the tBA concentrations were near the sample quantitation limits. Therefore, no qualification was added to the data.

Tetra Tech also conducted a cursory quality control review for the non-critical analytical variables. This review was performed to confirm the overall usability of the data in the evaluation of the secondary objectives. Based on this review, the non-critical data were assessed to be usable for their intended uses.

During the first demonstration sampling event, QA supervisory personnel conducted a Technical Systems Audit (TSA) of field sample collection and handling procedures. QA personnel also completed a TSA of the laboratory responsible for analyzing the critical VOC variables (MtBE, tBA, and BTEX). The field TSA also resulted in clarifications and modifications to the sampling procedures established in the QAPP. These generally involved minor changes to documentation practices, sampling schedules, sample containers, and sample identification number formats. In addition, the field TSA increased the frequency of trip blank collection from 5% of the treatment samples to 1 trip blank per cooler of VOC samples. Requirements to collect field blanks and source water blanks were removed.

The laboratory audit noted only one finding. The finding concerned an initial calibration (ICAL) for MtBE that failed to meet relative response factor (RRF) linearity criterion of RSD<15%. The laboratory dropped the 1 µg/L calibration standard from the ICAL curve to meet the relative standard deviation (RSD) criterion, which meant 5 µg/L was then the lowest calibration standard. This was inconsistent with QAPP requirements, and furthermore was technically unacceptable because 5 µg/L was the project treatment goal for MtBE, and it was desirable to accurately quantify MtBE below this level. The QAPP allows the laboratory to use a

linearity criterion of $r^2 > 0.99$ for the ICAL curve if the RSD criterion is not met. Therefore, as a corrective action, the laboratory added the 1 µg/L standard back into the curve, determined that the $r^2 > 0.99$ were met, and re-quantified the affected samples.

3   ECONOMIC ANALYSIS

This section presents cost estimates for using the E-Beam technology to treat groundwater contaminated with MtBE. Cost data were obtained during the demonstration at the NBVC, during the previous demonstration at the Savannah River Site, and from Haley and Aldrich. For comparability, these costs have been placed in the 12 categories applicable to typical cleanup activities at Superfund and RCRA sites (Evans 1990). Costs are considered to be order-of-magnitude estimates with an expected accuracy of from 50% above to 30% below actual costs. This section describes the applications selected for economic analysis, summarizes the major issues involved and assumptions made in performing the economic analysis, lists the costs associated with using the E-Beam technology in the selected applications, and then develops at a cost per unit volume of water treated for each application.

Two applications were selected for the economic analysis. The first application assumes the scenario of the demonstration at NBVC within the MTBE Source Zone, including the contaminant levels in the groundwater at that location and the treatment goals that were developed for the demonstration. This scenario is essentially a remedial application, since the levels of MTBE in the influent were much higher (about 2,000 µg/L) than would likely be treated for subsequent use as a drinking water source.

The second application is for a larger-scale utilization as part of a drinking water treatment plant, in which the E-beam system would be used to treat the groundwater to remove MtBE. The scale selected for this application is 10 MGD, which is intended to simulate a small drinking water treatment plant. In this scenario, a lower influent concentration of MTBE (200 µg/L) was assumed and the California secondary MCL for MTBE (5 µg/L) was assumed to be the applicable regulatory criterion for the treated water.

3.1   GENERAL ISSUES AND ASSUMPTIONS

Prior to presenting the cost estimates for each of the selected applications, it is important to describe how costs associated with an E-beam application can vary based on numerous factors, such as the type and scale of the application, contaminant types and levels, regulatory criteria, and site-specific factors. A discussion of some of the primary factors that affect the cost of an E-beam system is provided in Sections 3.1.1 through 3.1.4 below. A discussion of general assumptions utilized in the subsequent cost analysis is then provided in Section 3.1.5.

3.1.1   Type and Scale of Application

The E-beam system can be used both as a drinking water treatment technology and as a remedial technology. In a drinking water treatment application, the E-beam technology would typically be applied to treat organic contaminants, such as MtBE, that are not typically removed by conventional water treatment technologies. In a remedial application, the E-beam technology may be used to clean up contaminated groundwater at a RCRA corrective action or Superfund

site. Remedial applications will typically involve much higher costs per unit volume of water treated for several reasons:

- Site preparation costs may be significant as utilities and other infrastructure may not be immediately available at the site.

- Remedial applications are typically temporary installations and will therefore involve substantial mobilization and demobilization costs.

- Installation of well fields may be needed to extract the contaminated groundwater.

- Treatment volumes and the time period required to achieve site closure may not be certain.

- Permitting and other regulatory-driven costs may be higher due to the complex nature of site cleanups.

The scale of the application is a primary factor that affects the unit cost per volume of water treated for a technologically sophisticated system such as the E-beam. Larger scale applications incorporate substantial equipment cost savings on a cost per unit volume of water treated because the E-beam generator, equipment housings, control systems, and appurtenances are only slightly more expensive for larger E-beam systems. Labor costs are also proportionately lower due to the use of full-time, dedicated staff for equipment operations and maintenance.

3.1.2 Contaminant Types and Levels

As shown in the demonstration at NBVC and in previous demonstrations, some contaminants are relatively easy to destroy even at low E-beam doses, whereas other contaminants (such as tBA) are much more difficult to destroy, even at high doses. Further, the required E-beam dose increases with increasing contaminant concentrations in the influent water. Higher E-beam doses require larger scale E-beam generators and proportionately higher energy consumption.

3.1.3 Regulatory Criteria

Regulatory criteria for the treated water affect the same variables as contaminant types and levels. More stringent regulatory criteria for the treated water can greatly increase the dose required and the corresponding size of the E-beam system as well as the associated energy costs. Regulatory criteria also affect permitting costs and effluent monitoring (analytical) costs.

3.1.4 Site-specific Features

Site-specific features can affect the costs of using the E-Beam treatment system, particularly in remedial applications. Site features affecting costs include groundwater recharge rates, groundwater chemistry, site accessibility, availability of utilities, and geographic location. Groundwater recharge rates affect the time required for cleanup. Site accessibility, availability of utilities, and site location and size all affect site preparation costs.

3.1.5 General Assumptions

Certain assumptions were made to simplify the cost estimating for situations that actually would require complex engineering and financial considerations. The following general assumptions were made for the cost analysis that is presented subsequently:

- Costs are rounded to the nearest $100 and to the nearest $0.01 per 1,000 gallons.

- Equipment costs for the E-beam system are for the entire system, including control systems and appurtenances, and are as provided by Haley and Aldrich.

- Equipment costs are amortized linearly without interest over the period of projected operation and up to the projected useful life of these systems (20 years); no salvage value is assumed.

- An E-beam system will provide a dose of 1,000 krads to a 1.0-gpm stream at a 100 kW power input; this assumes an electrical energy input to absorbed radiation conversion efficiency of about 63%.

- The E-Beam equipment will be properly maintained and will continue to operate at the same efficiency for the assumed useful life of the equipment or for the duration of the groundwater treatment project, if less than 20 years.

- Operational labor costs $40 per hour, fully burdened (including office space, office equipment and supplies, and fringe benefits).

- Annual equipment maintenance costs are about 5% of the capital equipment costs, based on estimates provided by Haley and Aldrich.

- Electrical power costs $0.10 per kW-hr delivered to the site.

- The costs presented in the analysis below will need to be adjusted for applications where other assumptions are appropriate and for the site-specific contaminants and treatment goals of these applications.

3.2 REMEDIAL APPLICATION AT 10 GPM

The equipment and operational assumptions for the remedial application are listed below:

- A 21-kW E-beam system is used, similar to the existing trailer-mounted system, and is operated 24 hours per day, 7 days per week, 52 weeks per year for 10 years to clean up the contaminated groundwater.

- The treatment system operates at the full power of 21 kW (a voltage of 500 kV and a beam current of 42 mA).

- The groundwater to be treated is identical to that observed during the demonstration within the Source Zone at NBVC; thus, a dose of 2,000 krads is needed to destroy tBA (the rate limiting contaminant) to below the treatment goal of 12 µg/L in the effluent.

- The E-beam system is operated at a flow of 10 gpm, which is the maximum flow to achieve a dose of 2,000 krad at full power.

- The treatment system operates automatically without the constant attention of an operator and will shut down in the event of system malfunction.

- Modular components consisting of the equipment needed to meet treatment goals are mobilized to the site and assembled by Haley and Aldrich.

- The E-Beam system is mobilized to the site from within 1,000 miles of the site.

- Haley and Aldrich provides initial operator training and startup assistance to assure that the E-beam system functions properly.

- Air emissions monitoring is not necessary.

- A treatability study will be conducted by Haley and Aldrich to confirm dose requirements and other operational variables.

Table 3-1 summarizes the estimated costs for this application, and the sections below detail the basis for the cost calculations associated with each of the following 12 cost categories: (1) site preparation, (2) permitting and regulatory, (3) mobilization and startup, (4) equipment, (5) labor, (6) supplies, (7) utilities, (8) effluent treatment and disposal, (9) residual waste shipping and handling, (10) analytical services, (11) equipment maintenance, and (12) site demobilization.

3.2.1 Site Preparation Costs

Site preparation costs include administrative, treatment area preparation, treatability study, and system design costs. For this application, site preparation administrative costs, such as costs for legal searches, access rights, and site planning activities, are estimated to be $35,000.

Table 3-1. Economic Analysis of the Remedial Application at 10 gpm.

	21-kW E-Beam System (10 gallons per minute)		
		total	
	itemized (costs)	cost	cost/1,000 gallons
Site Preparation		$ 175,600	$ 3.34
Administrative	$ 35,000		
Treatment Area Preparation	$ 107,600		
Treatability Study and System Design	$ 33,000		
Permitting and Regulatory		$ 5,000	$ 0.10
Mobilization and Startup		$ 20,000	$ 0.38
Transportation	$ 10,000		
Assembly and Shakedown	$ 10,000		
Equipment		$ 842,000	$ 16.02
Labor		$ 20,800/yr	$ 3.95
Supplies		$ 1,700	$ 0.32
Disposable Personal Protective Equipment	$ 600		
Fiber Drums	$ 100		
Sampling Supplies	$ 1,000		
Utilities		$ 35,800/yr	$ 6.81
Effluent Treatment and Disposal		NA	$ -
Residual Waste Shipping and Handling		$ 600/yr	$ 0.11
Analytical Services		$ 7,200/yr	$ 1.37
Equipment Maintenance		$ 42,200/yr	$ 7.87
Site Demobilization		$ 15,000	$ 0.28
	Total Cost ($/1000 gallons)		$ 40.55

Treatment area preparation includes constructing a shelter building and installing pumps, valves, and piping from the extraction wells to the shelter building. The shelter building needs to be constructed before mobilization of the E-Beam system. A 400-square-foot building is required for the 21-kW system. Haley and Aldrich will provide the shelter building design specifications. Construction costs are estimated to be about $110 per square foot, which covers installation of radiation shielding materials. A natural gas heating and cooling unit and ductwork costs about $20,000 installed. The total shelter building construction costs for the 21-kW system are estimated to be $64,000.

This analysis assumes that four extraction wells are installed on site and that they are located 200 feet from the shelter building. Four 5-gpm, 0.5-horsepower, variable-speed pumps are required to pump contaminated groundwater from wells at a total flow rate of 10 gpm. The total well and pump costs, including all electrical equipment and installation, are $11,600. Piping and valve connection costs are about $40 per foot, which covers underground installation. Therefore, the total piping costs are $32,000. The total treatment area preparation costs are estimated to be $107,600.

It is assumed that Haley and Aldrich will transport its mobile system to the site to perform a treatability study and to test the equipment under site conditions. Six to eight samples will be collected from the influent and effluent and will be analyzed off site for VOCs. Haley and Aldrich estimates the treatability study cost to be $18,000, including labor and equipment costs. The treatability study includes determining appropriate E-Beam dose to achieve the treatment goals and designing the configuration. The system design is estimated to cost $15,000. Total site preparation costs are therefore estimated to be $175,600.

3.2.2 Permitting and Regulatory Costs

Permitting and regulatory costs depend on whether treatment is performed at a Superfund or a RCRA corrective action site and on how treated effluent and any solid wastes are disposed of. Superfund site remedial actions must be consistent with all applicable environmental laws, ordinances, regulations, and statutes, including federal, state, and local standards and criteria. Remediation at RCRA corrective action sites requires additional monitoring and record keeping, which can increase the base regulatory costs. In general, applicable or relevant and appropriate requirements (ARARs) must be determined on a site-specific basis. Permitting and regulatory costs in this analysis include permit fees for discharging treated water to a surface water body. The cost of this permit would be based on regulatory agency requirements and treatment goals for a particular site. The discharge permit is estimated to cost $5,000.

3.2.3 Mobilization and Startup Costs

Mobilization and startup costs include the costs of transporting the E-Beam system to the site, assembling the E-Beam system, and performing the initial shakedown of the treatment system. Haley and Aldrich provides trained personnel to assemble and conduct preliminary tests on the E-Beam system. Haley and Aldrich personnel are trained in hazardous waste site health and safety procedures, so health and safety training costs are not included as a direct startup cost. Initial operator training is needed to ensure safe, economical, and efficient operation of the system. Haley and Aldrich provides initial operator training to its clients as part of providing the E-Beam equipment. Transportation costs are site-specific and vary depending on the location of

the site in relation to the equipment. For this analysis, the E-Beam equipment is assumed to be transported 1,000 miles. Haley and Aldrich retains the services of a cartage company to transport all E-Beam treatment system equipment. Mobilization costs are about $10 per mile for a total cost of $10,000. The costs of highway permits for overweight vehicles are included in this total cost. Assembly costs include the costs of unloading equipment from the trailers, assembling the E-Beam system, hooking up extraction well piping, and hooking up electrical lines. A two-person crew will work three 8-hour days to unload and assemble the system and perform the initial shakedown. The total startup costs are about $10,000, including labor and hookup costs. Total mobilization and startup costs are therefore estimated to be $20,000.

3.2.4   Equipment Costs

Haley and Aldrich estimates that the capital equipment cost is $842,000 for a 21-kW system.

3.2.5   Labor Costs

Once the system is functioning, it is assumed to operate continuously at the designed flow rate except during routine maintenance. One operator trained by Haley and Aldrich performs routine equipment monitoring and sampling activities. Under normal operating conditions, an operator is required to monitor the system about once each week. This analysis assumes that the work is conducted by a full-time employee of the site owner and is assigned to be the primary operator to perform system monitoring and sampling duties. Further, it is assumed that a second person, also employed by the site owner, will be trained to act as a backup to the primary operator. Based on observations made at the NBVC demonstration, it is estimated that operation of the system requires about 10 hours per week of a primary operator's time. Assuming that the primary operator's burdened labor rate is $40 per hour, the total annual labor cost is estimated to be $20,800.

3.2.6   Supply Costs

No chemicals or treatment additives are expected to be needed to treat the groundwater using the E-Beam technology. Therefore, no direct supply costs are expected to be incurred. Supplies that will be needed as part of the overall groundwater remediation project include Level D, disposable personal protective equipment (PPE), PPE disposal drums, and sampling and field analytical supplies. Disposable PPE typically consists of latex inner gloves, nitrile outer gloves, radiation badges, and safety glasses. This PPE is needed during periodic sampling activities. Disposable PPE for is assumed to cost about $600 per year for the primary operator. Used PPE is assumed to be hazardous and needs to be disposed of in 24-gallon, fiber drums. One drum is assumed to be filled every 2 months, and each drum costs about $12. The total annual drum costs rounded to the nearest $100 are about $100.

Sampling supplies consist of sample bottles and containers, ice, labels, shipping containers, and laboratory forms for off-site analyses. For routine monitoring, laboratory glassware is also needed. The numbers and types of sampling supplies needed are based on the analyses to be performed. Costs for laboratory analyses are presented in Section 3.2.10. The sampling supply costs are estimated to be $1,000 per year. Total annual supply costs are estimated to be $1,700.

3.2.7 Utility Costs

Electricity is the only utility used by the E-Beam system. Electricity is used to run the E-Beam treatment system, pumps, blower, and air chiller. This analysis assumes that electrical power lines are available at the site. Electricity costs can vary considerably depending on the geographical location of the site and local utility rates. Also, the consumption of electricity varies depending on the E-Beam system used, the total number of pumps and other electrical equipment operating, and the use of the air chiller.

This analysis assumes a constant rate of electricity consumption based on the electrical requirements of the E-Beam treatment system (21-kW). The pumps, blower, and air chiller are assumed to draw an additional 20 kW. Therefore, the 21-kW unit operating for 1 hour draws about 41 kW hours (kWh) of electricity. The total annual electrical energy consumption is estimated to be about 358,176 kWh. Electricity is assumed to cost $0.10 per kWh, including demand and usage charges. The total annual electricity costs are therefore estimated to be about $35,800.

3.2.8 Effluent Treatment and Disposal Costs

Depending on the treatment goals for a site, additional effluent treatment may be required, and thus additional treatment or disposal costs may be incurred. Because of the uncertainty associated with additional treatment or disposal costs, this analysis does not include effluent treatment or disposal costs. The E-Beam system does not produce air emissions because the water delivery and cooling air systems are enclosed. As a result, no cost for air emissions treatment is incurred. It is assumed that the primary operator routinely conducts effluent monitoring. The effluent can be discharged directly to a nearby surface water body, provided that appropriate permits have been obtained (see Section 3.2.2).

3.2.9 Residual Waste Shipping and Handling Costs

The only residuals produced during E-Beam system operation are fiber drums containing used PPE and waste sampling and field analytical supplies, all of which are typically associated with a groundwater project. This waste is assumed to be non-hazardous with associated disposal at a non-hazardous waste landfill. This analysis assumes that about six drums of waste are disposed of annually. The cost of handling and transporting the drums and disposing of them at a non-hazardous waste disposal facility is about $100 per drum. The total drum disposal costs are therefore about $600 per year.

Condensate is generated from the air chiller. This condensate can be treated by the E-Beam system, but such treatment may require additional permits from regulatory authorities. Because of the uncertainty associated with the need for additional permits, the costs for such additional permits were not included in this analysis.

3.2.10 Analytical Services Costs

Required sampling frequencies are highly site specific and are based on treatment goals and contaminant concentrations. Analytical costs associated with a groundwater treatment project include the costs of laboratory analyses, data reduction, and QA/QC. This analysis

assumes that one sample of untreated water, one sample of treated water, and associated QC samples (trip blanks, field duplicates, and matrix spike/matrix spike duplicates) will be analyzed for VOCs every month. Monthly analytical costs are estimated at $600. The total annual analytical costs are therefore estimated to be $7,200.

3.2.11 Equipment Maintenance Costs

Haley and Aldrich estimates that annual equipment maintenance costs are about 5% of the capital equipment costs. Therefore, the total annual equipment maintenance costs are about $42,200 for the 21-kW system.

3.2.12 Site Demobilization Costs

Site demobilization includes treatment system shutdown, disassembly, and decontamination; site cleanup and restoration; utility disconnection; and transportation of the E-Beam equipment off site. A two-person crew will work about five 8-hour days to disassemble and load the system. This analysis assumes that the equipment will be transported 1,000 miles either for storage or to the next job site. Haley and Aldrich estimates that the total cost of demobilization is about $15,000. This total includes all labor, material, and transportation costs.

3.3 DRINKING WATER TREATMENT APPLICATION AT 10 MGD

The equipment and operating parameter assumptions for the larger-scale drinking water treatment application are based on a recent treatability study performed by Haley and Aldrich using groundwater contaminated with MtBE from Santa Monica, California, as reported by Haley and Aldrich (Nickelsen, 2002). Approximately 1,800 gallons of groundwater from Santa Monica was transported in a clean tanker truck and treated in the 21-kW trailer-mounted E-beam system that was still on site at NVBC. Due to low native concentrations of MtBE in the Santa Monica groundwater, the water was spiked with 200 μg/L MtBE in one experiment intended to simulate a drinking water supply recently contaminated with MtBE. In this experiment, a dose of 167 krads (the lowest dose tested) was sufficient to remove MtBE to well below the treatment goal of 5 μg/L without increasing the concentration of TBA to above 12 μg/L. This scenario was assumed as the basis for the economic analysis below.

The equipment and operational assumptions for the drinking water treatment application are listed below:

- The treatment system processes 10 MGD and is operated 24 hours per day, 7 days per week, 52 weeks per year for 20 years (the useful life of the equipment).

- A dose of 167 krads is required, which can be provided using with twelve 100-kW E-beam systems for a flow of 10 MGD.

- Modular components consisting of the equipment needed to meet treatment goals are mobilized to the site and assembled by Haley and Aldrich.

- Haley and Aldrich provides initial operator training and startup assistance to ensure that the E-beam system functions properly.

- A treatability study is conducted by Haley and Aldrich to confirm dose requirements and other operational variables.

- Air emissions monitoring is not necessary.

Table 3-2 summarizes the estimated costs for this application. The assumptions associated with the cost analysis, which emphasizes the differences from the remedial application, are summarized below:

- The capital equipment cost of each 100-kW E-beam system is $1.5 million, fully installed.

- The following site preparation costs are estimated as percentages of the capital equipment cost: administration, 1%; site preparation, 3%; and system design (including the treatability study), 6%.

- Two full-time operators are required to ensure proper functioning of the treatment system.

- Permitting and regulatory costs are $50,000.

- Shakedown and start-up costs are $700,000.

- Supply and residual waste handling costs are eight times that of the remedial scenario (proportional to operating labor hours).

- Electrical energy demand for the treatment system includes 1,200 kW for the beams themselves and 600 kW for the associated blowers, pumps, and appurtenances.

- Laboratory analysis support requirements assume that one sample of untreated water, one sample of treated water, and associated QC samples will be analyzed for VOCs every day at a cost of $600 per day.

- Equipment transportation costs are included in the installed equipment cost item and there is no demobilization cost.

Table 3-2. Economic Analysis of the Drinking Water Treatment Application at 10 MGD.

| | | 1200-kW E-Beam System (10 MGD) | | |
| | | | total | |
	itemized (costs)	cost	cost/1,000 gallons
Site Preparation		$ 1,720,000	$ 0.02
Administrative	$ 180,000		
Treatment Area Preparation	$ 540,000		
Treatability Study and System Design	$ 1,080,000		
Permitting and Regulatory		$ 50,000	$ 0.00
Mobilization and Startup		$ 700,000	$ 0.01
Transportation	NA		
Shakedown and Startup	$ 700,000		
Equipment		$ 18,000,000	$ 0.25
Labor		$ 163,200/yr	$ 0.04
Supplies		$ 13,600	$ 0.00
Disposable Personal Protective Equipment	$ 4,800		
Fiber Drums	$ 800		
Sampling Supplies	$ 8,000		
Utilities		$ 1,576,800/yr	$ 0.43
Effluent Treatment and Disposal		NA	$ -
Residual Waste Shipping and Handling		$ 4,800/yr	$ 0.00
Analytical Services		$ 219,000/yr	$ 0.06
Equipment Maintenance		$ 900,000/yr	$ 0.25
Site Demobilization	NA		
Total Cost ($/1000 gallons)			$ 1.06

NA = Not applicable.

4   TECHNOLOGY APPLICATIONS ANALYSIS

This section of the report describes the general applicability of the E-Beam technology, operated by Haley and Aldrich, for treating contaminated groundwater at hazardous waste and petroleum release sites. The analysis is based primarily on the demonstration results at the NBVC; however, the demonstration results are supplemented by data from other applications of the E-Beam technology, including a study conducted in Germany with the E-Beam system and a demonstration conducted at the U.S. Department of Energy Savannah River Site in Aiken, South Carolina under the EPA Superfund Innovative Technology Evaluation (SITE) demonstration program (EPA 1997). Vendor's claims regarding the effectiveness and applicability of the E-Beam technology are included in Appendix A.

This section also discusses the following topics regarding the applicability of the E-Beam technology: technology performance versus ARARs, technology operability, key features of the treatment technology, applicable wastes, availability and transportability of equipment, material handling requirements, range of suitable site characteristics, limitations of the technology, and potential regulatory requirements.

4.1   TECHNOLOGY PERFORMANCE VERSUS ARARS

The technology's ability to comply with existing federal, state, or local ARARs (for example, MCLs) should be determined on a site-specific basis, as is the case with all innovative

technologies. The discussion below focuses on the demonstration at the NBVC for MtBE-contaminated groundwater.

For the demonstration at the NBVC, ARARs were identified and established by consensus among the stakeholders for the technology demonstration. ARARs included EPA and California Primary and Secondary MCLs as well as California Action Levels and Public Health Goals for drinking water. The contaminants initially present in the groundwater were of primary concern; these included MtBE and BTEX. Partially oxidized organics from MtBE degradation (tBA, acetone, aldehydes, glyoxals) were also of concern. In addition, several drinking water variables were identified as applicable if the effluent was to be used as a drinking water supply. These drinking water variables included bromate, a by-product of chemical oxidation, and potential by-products of subsequent chlorination, including total TTHM and HAA. For the by-products of subsequent chlorination, the applicable criteria are described in the proposed Stage 2 DBPR. These requirements have been proposed in a Notice of Agreement in Principle dated December 20, 2000 (65 FR 251, pages 83015-83024).

In the demonstration at the NBVC, the E-Beam technology met the treatment goals for the primary contaminants of concern. However, reaction by-products from MtBE, BTEX and other constituents of gasoline (tBA, acetone, aldehydes, and glyoxals) remained in the effluent and were higher in concentration than some potentially applicable ARARs. Also, the technology did not meet the drinking water requirements relating to TTHMs and HAAs in SDS testing of the effluent. In the Phase 2 studies where a dose response was developed, it is likely that, if a slightly higher dose had been chosen (about 2,000 krads), tBA would have been below the action level. Because the other reaction by-products (acetone, aldehydes, and glyoxals) were not determined, it is not clear whether they would have met the target treatment concentrations.

The results of the previous demonstration of the E-Beam system at the Savannah River Site provided information with respect to chlorinated hydrocarbon contaminants in groundwater. During the demonstration, the E-Beam system treated about 70,000 gallons of groundwater contaminated with VOCs, including TCE and PCE, which were present at concentrations of about 27,000 and 11,000 µg/L, respectively. The groundwater also contained low levels (40 μg/L) of cis-1,2-dichloroethene (1,2-DCE). Other commonly encountered groundwater contaminants, including BTEX and other chlorinated hydrocarbons, were spiked into the influent during part of the demonstration at levels of 500 to 1,000 µg/L. The E-Beam system achieved the effluent target levels for 1,2-DCE, carbon tetrachloride, and BTEX; however, effluent target levels were not achieved for TCE, PCE, 1,1,1-trichloroethane, 1,2-dichloroethane, and chloroform. The results from bioassay tests indicate that treatment by the E-Beam technology increased groundwater toxicity to fathead minnows but not to water fleas.

In summary, the E-Beam technology has been shown to be capable of destroying many commonly encountered organic contaminants in groundwater to below applicable drinking water regulatory criteria in California. For hydrocarbons, including BTEX and MtBE, effluent compliance with these criteria appears to be well within the capabilities of the technology. At high concentrations of chlorinated hydrocarbons, problems may be encountered if MCLs are established as the effluent requirements. Additionally, partially oxidized organic compounds and other chemical oxidation by-products may be of concern to ARAR compliance at specific sites, depending on the application and the planned disposal or reuse of the effluent from the E-Beam

system. Future ARARs relating to these types of contaminants are being contemplated and may take the form of either chemical specific or bioassay requirements.

The following were identified as additional potential technology performance issues with respect to ARARs:

- The technology's ability to meet any future chemical-specific ARARs for by-products should be considered because of the potential for formation of partially oxidized organic compounds during treatment. Properly designed pilot testing will define variables to be considered.

- The technology's ability to meet any state or local requirements such as passing bioassay tests should be considered because of the potential for treatment by-product formation. Properly designed pilot testing will define variables and alternatives for meeting all of the local, state and federal requirements.

- States require notification and registration for system operation

- Design, construction, operation, and maintenance of the system must comply with general radiation exposure regulations, Over 500 accelerators exist in the US, and all of the States have regulations in place that specify operation. Examples of applications are medical device sterilization and, more recently, food irradiation facilities.

4.2   TECHNOLOGY OPERABILITY

Operating variables are those variables that can be varied during the treatment process to achieve desired removal efficiencies and treatment goals. The principal factor affecting E-Beam system performance is the E-Beam dose. The dose can be varied, within the equipment limits of each accelerator, by varying the beam current (in the demonstration system it was variable from 0 - 42 mA) and water flow rate (in the demonstration system it was variable from 5 - 40 gpm). Therefore, dose depends on E-Beam power and water flow rate.

In a typical continuous flow treatment system, the absorbed dose can be determined by measuring the temperature difference of the water stream before and after irradiation. The relationship is derived for pure water by the following relationships:

$$1 \text{ rad} = 100 \text{ erg g}^{-1} \text{ (or } 1 \text{ Mrad} = 1.0 \text{ x } 10^8 \text{ erg g}^{-1}) \qquad [2]$$

substituting in,

$$1 \text{ erg} = 2.39 \text{ x } 10^{-8} \text{ cal} \qquad [3]$$

then,

$$1 \text{ Mrad} = 2.39 \text{ cal g}^{-1} \qquad [4]$$

converting to °C,

$$1 \text{ Mrad} = 2.39°C = 10 \text{ kGy} \qquad [5]$$

or,

$$°T = 0.418 \text{ Mrad or } 4.18 \text{ kGy }°C^{-1} \hspace{4cm} [6]$$

The relationship between dose and temperature is one way to estimate relative energy consumed for the treatment of a compound(s). It provides an estimate of the temperature increase in the treated solution, and this can then be related to energy (and cost) for the treatment. As the beam current passes through a tungsten wire filament within the electron accelerator, a stream of electrons is emitted that comprises the E-Beam. The number of electrons emitted per unit time is proportional to the beam current. Therefore, for a given flow rate, dose is increased by increasing the beam current, which increases the number of electrons impacting the liquid and, consequently, the number of reactive species formed. The electron accelerator in the E-Beam system used for the demonstration is capable of generating a maximum beam current of about 42 mA. The beam current is adjusted and monitored at the control panel in the E-Beam trailer control room.

Flow rate through the treatment system determines the length of time the water is exposed to the E-Beam. In general, increasing the exposure time (decreasing the flow rate) improves treatment efficiency by increasing the number of reactive species formed as more high-speed electrons impact a discrete volume of water. If treatment goals are not met, increasing the beam current or adjusting the influent delivery system can improve treatment efficiency. The flow rate provided by the influent pump is monitored and adjusted in the E-Beam trailer pump room.

The voltage applied to the E-Beam affects the depth to which the E-Beam penetrates the water being treated. At a given E-Beam penetration depth, the portion of flowing water directly irradiated by the beam depends on the thickness of the flowing water. Adjusting the influent delivery system for the E-Beam unit can control the thickness of the flowing water. The internal components of the delivery system and its dimensions are proprietary information.

4.3   KEY FEATURES OF THE TREATMENT TECHNOLOGY

Common methods for treating groundwater contaminated with organic compounds include air stripping, steam stripping, carbon adsorption, biological treatment, and chemical oxidation. As regulatory requirements for secondary wastes and treatment by-products become more stringent and more expensive to comply with, technologies involving free radical chemistry offer a major advantage over other treatment techniques: these technologies destroy contaminants rather than transfer them to another medium, such as activated carbon or the ambient air. Technologies involving free radical chemistry offer faster reaction rates than other technologies, such as some biological treatment processes. According to the published literature (Buxton et al., 1988), the entire sequence of reactions between organic compounds and reactive species occurs in the area where the E-Beam impacts the water and is completed in milliseconds.

The E-Beam technology generates strong reducing species (e^-_{aq} and •H) and strong oxidizing species (•OH) simultaneously and in approximately equal concentrations. Because three reactive species are formed, multiple mechanisms or chemical pathways for organic compound destruction are provided. In this way, the E-Beam technology differs from other

technologies that involve free radical chemistry. Such technologies typically rely on a single organic compound destruction mechanism, usually one involving •OH.

The E-Beam system does not generate residue, sludge, or spent media that require further processing, handling, or disposal. Most of the target organic compounds are either mineralized or broken down into low molecular weight compounds. Radicals generated by the E-beam react with contaminants to produce intermediate species that are ultimately oxidized to CO_2, water, and salts. However, incomplete oxidation results in formation of low molecular weight aldehydes, glyoxals, organic acids, and SVOCs, one of which is tBA. If the MtBE concentration in the water being treated is high enough, then tBA production from MtBE oxidation by E-beam might render the effluent non-compliant with tBA objectives.

4.4   APPLICABLE WASTES

Based on the NBVC and Savannah River Site demonstration results, as well as results from other case studies and published accounts of studies conducted at up to 120 gpm, the E-Beam technology may be used to treat various VOCs and SVOCs in liquids, including groundwater (with solids content of up to 5 %), wastewater, biosolids, drinking water, and landfill leachate. Where stringent effluent requirements apply, the technology appears to be particularly applicable to the treatment of contaminated groundwater and wastewater containing petroleum hydrocarbons. However, the technology can achieve substantial reductions in the concentrations of other organic compounds. The following is a partial listing of various solutions with one or more organic contaminants:

1.   General organic compounds (Kurucz et al., 1991a; 1991b)
2.   BTEX (Nickelsen et al., 1992; 1994; Zele et al., 1998
3.   THMs, dichloromethane, and carbon tetrachloride (Mak et al., 1996; 1997)
4.   Phenol (Lin et al., 1995)
5.   Naphthalene (Cooper et al., 2002)
6.   Alternative Fuel Oxygenates (Mezyk et al., 2001)
7.   Chemical Warfare Agent-Simulants (Nickelsen et al., 1998)

4.5   AVAILABILITY AND TRANSPORTABILITY OF EQUIPMENT

Haley and Aldrich provides the complete E-Beam treatment system configured for site-specific conditions. All E-Beam treatment equipment is leased to the client. As a result, all depreciation and salvage value is incurred by Haley and Aldrich, which is reflected in the price for leasing the equipment. At the end of a treatment project, Haley and Aldrich decontaminates and demobilizes its treatment equipment. Haley and Aldrich assumes that this equipment will operate for the duration of the groundwater remediation project and will still function after the remediation is complete as a result of routine maintenance and modifications.

Currently, only one mobile treatment system has been constructed and is available through Haley and Aldrich for application to site-specific requirements. However, for larger remediation projects, it is more cost effective to construct a fixed treatment system at the site.

4.6   MATERIALS HANDLING REQUIREMENTS

Other than the spent filter media when pretreatment processing is used in the influent delivery system, the E-Beam system does not generate treatment residuals, such as sludge, that requires further processing, handling, or disposal. The E-Beam unit and the other components of the system produce no air emissions that require specific controls. Pretreatment processing typically involves cartridge or sand filters to remove suspended solids. Spent filter media or other residuals from these systems should be dewatered, containerized, and analyzed to determine whether they should be disposed of as hazardous or non-hazardous waste.

Treated water may be disposed of either on or off site, depending on site-specific requirements and limitations. Examples of on-site disposal options for treated water include groundwater recharge or temporary on-site storage for sanitary use. Examples of off-site disposal options include discharge into surface water bodies, storm sewers, and sanitary sewers. Bioassay tests may be required in addition to routine chemical and physical analyses before the treated water is disposed of.

4.7   RANGE OF SUITABLE SITE CHARACTERISTICS

In addition to feed waste characteristics and effluent discharge requirements, site characteristics and support requirements are important when considering the E-Beam technology. Site-specific factors can impact the application of the E-Beam technology, and these factors should be considered before selecting the technology for remediation of a specific site. Site-specific factors addressed in this section include site support requirements and utility requirements.

According to Haley and Aldrich, both transportable and permanently installed E-Beam systems are available (see Section 5, Technology Status, and Appendix A, Vendor's Claims for the Technology). The support requirements for these systems are likely to vary. This section presents support requirements based on the information collected for the trailer-mounted system used during the demonstration.

4.7.1   Site Support Requirements

The site must be accessible for a tractor-trailer truck with an 8-foot by 48-foot trailer weighing about 35 tons. An area of 8 feet by 48 feet must be available for the trailer that houses the E-Beam system, and additional space must be available to allow personnel to move freely around the outside of the trailer. The area containing the E-Beam trailer should be paved or covered with compacted soil or gravel to prevent the trailer from sinking into soft ground. The trailer is equipped with a 500-gallon influent holding tank and an effluent holding tank with a capacity of about 100 gallons, but space outside the trailer may be required for additional influent and effluent holding tanks if more holding capacity is needed. An additional area may be required for an office or laboratory building or trailer. During the demonstration, an area of about 100 feet by 200 feet was used for the E-Beam trailer, an outdoor staging area, and miscellaneous equipment.

The E-Beam trailer is equipped with influent and effluent ports on the exterior trailer wall. The influent port is plumbed to an influent pump in the pump room that is rated for a

maximum flow rate of 40 gpm, and the effluent port is plumbed from the effluent holding tank. Plumbing must be provided to the influent port from the groundwater well or other feed waste source and from the effluent port to the discharge point.

4.7.2 Utility Requirements

The E-Beam system may be operated using 480-volt, 3-phase electrical service. The E-Beam trailer is also equipped with a diesel-powered generator that allows the system to be operated without an external electrical source. Additional electrical service may be needed to operate groundwater extraction well pumps, light office and laboratory buildings, and on-site office and laboratory equipment, as applicable. Haley and Aldrich maintains and services its E-Beam systems; therefore, no inventory of spare parts is required.

4.8 LIMITATIONS OF THE TECHNOLOGY

Three limiting factors have been identified based on the operation of the Haley and Aldrich demonstration unit: limited operating flow rates, by-product formation, and operational problems associated with suspended solids in the influent. System operation is limited by the minimum and maximum flow rates at which a single unit can be operated. If treatment goals are not met while the system operates at the minimum flow rate and at maximum beam current, the dose cannot be further increased to improve system performance. Such a case would require operating additional E-Beam units in series, obtaining a larger E-Beam unit, or adding pretreatment or post-treatment, any of which would increase space requirements and costs. According to Haley and Aldrich, the demonstration unit was configured for a maximum flow rate of 40 gpm. Treatment at a higher flow rate would require modifying the influent delivery system for the unit, operating additional units in parallel, or obtaining a larger unit rated for a greater maximum flow rate; the latter two options would increase space requirements and costs. Based on research studies performed by Haley and Aldrich and demonstration results, toxic by-products are formed when water containing VOCs is treated by the E-Beam system. If by-products are a concern at a particular site, the E-Beam system would need to be operated in such a way that by-product formation would be reduced to acceptable levels. A third limiting factor involves the presence of suspended solids in the influent. Fine suspended solids not captured by the strainer basket might clog the influent delivery system for the E-Beam unit.

4.9 POTENTIAL REGULATORY REQUIREMENTS

This section discusses regulatory requirements pertinent to use of the E-Beam technology at Superfund and RCRA corrective action sites. The regulations applicable to implementation of this technology depend on site-specific remediation logistics and the type of contaminated liquid being treated; therefore, this section presents a general overview of the types of federal regulations that may apply under various conditions. State requirements should also be considered; because these requirements vary from state to state, they are not presented in detail in this section.

Depending on the characteristics of the liquid to be treated, pretreatment or post-treatment may be required for the successful operation of the E-Beam system. For example, solids may need to be filtered before treatment; a strainer basket was used to remove particulates larger than 0.045 inch during the demonstration. Each pretreatment or post-treatment process

might involve additional regulatory requirements that would need to be determined in advance. No direct air emissions or residuals (such as sludge) are generated by the E-beam treatment process. Condensate is generated from the cooling air when it enters the air chiller, but Haley and Aldrich states that this liquid can be recirculated through the system. Therefore, only regulations addressing contaminated liquid storage, treatment, and discharge; potential fugitive air emissions; and additional considerations are discussed below.

4.9.1 Resource Conservation and Recovery Act

RCRA, as amended by the Hazardous and Solid Waste Amendments of 1984, regulates management and disposal of municipal and industrial solid wastes. EPA and RCRA-authorized states (listed in 40 Code of Federal Regulations [CFR] Part 272) implement and enforce RCRA and state regulations. Some of the RCRA requirements under 40 CFR Part 264 generally apply at Comprehensive Emergency Response, Compensation, and Liability Act (CERCLA) sites that contain RCRA hazardous waste because remedial actions generally involve treatment, storage, or disposal of hazardous waste.

According to Haley and Aldrich, the E-Beam system can treat liquid contaminated with most organic compounds, including solvents, pesticides, PAHs, and petroleum hydrocarbons. Contaminated liquid treated by the system may be classified as a RCRA hazardous waste or may be sufficiently similar to a RCRA hazardous waste that RCRA regulations will be applicable requirements.

4.9.2 Clean Water Act

The Clean Water Act (CWA) is designed to restore and maintain the chemical, physical, and biological quality of navigable surface waters by establishing federal, state, and local discharge standards. If treated liquid is discharged to surface water bodies or publicly owned treatment works (POTW), CWA regulations apply. On-site discharges to surface water bodies must meet substantive National Pollutant Discharge Elimination System (NPDES) requirements but do not require an NPDES permit. A direct discharge of (CERCLA) wastewater would qualify as "onsite" if the receiving water body is in the area of contamination or in close proximity to the site, and if the discharge is necessary to implement the response action. Off-site discharges to a surface water body require a NPDES permit and must meet NPDES permit limits. Discharge to a POTW is considered to be an off-site activity, even if an on-site sewer is used. Therefore, compliance with substantive and administrative requirements of the National Pretreatment Program is required in such a case. General pretreatment regulations are included in 40 (CFR) Part 403.

Any applicable local or state requirements, such as local or state pretreatment requirements or water quality standards (WQS), must also be identified and satisfied. State WQS are designed to protect existing and attainable surface water uses (for example, recreation and public water supply). WQS include surface water use classifications and numerical or narrative standards (including effluent toxicity standards, chemical-specific requirements, and bioassay requirements to demonstrate no observable effect level [NOEL] from a discharge) (EPA, 1988a). These standards should be reviewed on a state- and location-specific basis before discharges are made to surface water bodies.

4.9.3   Safe Drinking Water Act

The Safe Drinking Water Act (SDWA), as amended in 1986, required EPA to establish regulations to protect human health from contaminants in drinking water. EPA has developed the following programs to achieve this objective: (1) a drinking water standards program, (2) an underground injection control program, and (3) sole-source aquifer and well-head protection programs.

SDWA primary (or health-based) and secondary (or aesthetic) MCLs generally apply as clean-up standards for water that is, or may be, used as drinking water. In some cases, such as when multiple contaminants are present, more stringent maximum contaminant level goals (MCLG) may be appropriate. In other cases, alternate concentration limits (ACL) based on site-specific conditions may be applied. CERCLA and RCRA standards and guidance should be used in establishing ACLs (EPA 1987a). During the SITE demonstrations, Haley and Aldrich treatment system performance was tested for compliance with SDWA MCLs for several critical VOCs.

The underground injection control program regulates water discharge through injection wells. Injection wells are categorized as Classes I through V, depending on their construction and use. Reinjection of treated water involves Class IV (reinjection) or Class V (recharge) wells and should meet SDWA requirements for well construction, operation, and closure. If the groundwater treated is a RCRA hazardous waste, the treated groundwater must meet RCRA Land Disposal Restriction (LDR) treatment standards (40 CFR Part 268) before reinjection.

The sole-source aquifer and wellhead protection programs are designed to protect specific drinking water supply sources. If such a source is to be remediated using the E-Beam system, appropriate program officials should be notified, and any potential regulatory requirements should be identified. State groundwater anti-degradation requirements and WQS may also apply.

4.9.4   Clean Air Act

The Clean Air Act (CAA), as amended in 1990, regulates stationary and mobile sources of air emissions. CAA regulations are generally implemented through combined federal, state, and local programs. The CAA includes chemical-specific standards for major stationary sources that would not be applicable but could be relevant and appropriate for E-Beam system use. For example, the E-Beam system would usually not be a major source as defined by the CAA, but it could emit ozone , which is a criteria pollutant under the CAA's National Ambient Air Quality Standards (NAAQS). Therefore, the E-Beam system may need to be controlled to ensure that air quality is not impacted. This would be particularly pertinent in localities that are "non-attainment" areas for ozone . The National Emission Standards for Hazardous Air Pollutants (NESHAP) could also be relevant and appropriate if regulated hazardous air pollutants are emitted and if the treatment process is considered sufficiently similar to one regulated under these standards. In addition, New Source Performance Standards (NSPS) could be relevant and appropriate if the pollutant emitted and the E-Beam system are sufficiently similar to a pollutant and source category regulated by an NSPS. Finally, state and local air programs have been delegated significant air quality regulatory responsibilities, and some have developed programs

to regulate toxic air pollutants (EPA 1989). Therefore, state air programs should be consulted regarding E-Beam treatment technology installation and use.

4.9.5   Toxic Substances Control Act

Testing, pre-manufacture notification, and record-keeping requirements for toxic substances are regulated under the Toxic Substances Control Act (TSCA). TSCA also includes storage requirements for polychlorinated biphenyls (PCB) (see 40 CFR §761.65). The E-Beam system may be used to treat liquid contaminated with PCBs, and TSCA requirements would apply to pretreatment storage of PCB-contaminated liquid.

4.9.6   Mixed Waste Regulations

As defined by the Atomic Energy Act (AEA) and RCRA, mixed waste contains both radioactive and hazardous components. Such waste is subject to the requirements of both acts. However, when application of both AEA and RCRA regulations results in a situation that is inconsistent with the AEA (for example, an increased likelihood of radioactive exposure), AEA requirements supersede RCRA requirements (EPA 1988a). Use of the Haley and Aldrich E-Beam system at sites with radioactive contamination might involve treatment or generation of mixed waste.

Office of Solid Waste and Emergency Response (OSWER), in conjunction with the NRC, has issued several directives to assist in identification, treatment, and disposal of low-level radioactive, mixed waste. Various OSWER directives include guidance on defining, identifying, and disposing of commercial, mixed, low-level radioactive and hazardous waste (EPA 1987b). If the Haley and Aldrich system is used to treat low-level mixed waste, these directives should be considered. If high-level mixed waste or transuranic mixed waste is treated, internal DOE orders should be considered when developing a protective remedy (DOE 1988). The SDWA and CWA also contain standards for maximum allowable radioactivity levels in water supplies.

4.9.7   Occupational Safety and Health Act

OSHA regulations in 29 CFR Parts 1900 through 1926 are designed to protect worker health and safety. Both Superfund and RCRA corrective actions must meet OSHA requirements, particularly §1910.120, Hazardous Waste Operations and Emergency Response. Part 1926, Safety and Health Regulations for Construction, applies to any on-site construction activities. For example, electric utility hookups for the Haley and Aldrich E-Beam system must comply with Part 1926, Subpart K, Electrical. Product chemicals, such as sulfuric acid and sodium hydroxide, if used with the E-Beam system, must be managed in accordance with OSHA requirements (for example, Part 1926, Subpart D, Occupational Health and Environmental Controls, and Subpart H, Materials Handling, Storage, and Disposal). Any more stringent state or local requirements must also be met. In addition, health and safety plans for site remediation should address chemicals of concern and include monitoring practices to ensure that worker health and safety are maintained.

4.10 Additional Considerations

The Haley and Aldich system generates a high-energy stream of electrons (ionizing radiation). These electrons are primarily directed to a contaminated liquid stream. However, some other radiation (x-ray) is generated when stray electrons hit metal components of the system. Therefore, regulations covering radiation-generating equipment could be considered ARARs. At the Savannah River Site, DOE regulations for radiation-generating equipment were applied. However, the Haley and Aldrich system is totally enclosed, and with adequate lead shielding of the E-Beam trailer, radiation monitoring did not reveal any OSHA compliance problems. Most equipment of this nature is regulated at a state level (for example, X-ray and other medical and laboratory equipment). Relevant standards for protection against radiation are included in the NRC regulations of 10 CFR Part 20. These standards are designed to limit radiation hazards caused by NRC-licensed activities. The regulations apply to all NRC licensees regardless of the type or quantity of radioactive material possessed or the type of operations conducted. These regulations require that (1) levels of radiation and dose be "as low as is reasonably achievable," and (2) radiation exposure limits for worker and public protection in 10 CFR Part 20 be met. Additional state-specific requirements should also be considered.

4.10.1 State and Community Acceptance

Because few applications of the E-Beam technology have been attempted beyond the bench or pilot scale, limited information is available to assess state and community acceptance of the technology. During the SITE demonstrations at the NBVC and the Savannah River Site, more than 100 people from regulatory agencies, nearby universities, and the local community attended Visitors' Day to observe demonstration activities and ask questions pertaining to the technology. The visitors expressed no concerns regarding operation of the E-Beam system.

5   TECHNOLOGY STATUS

According to Haley and Aldrich, E-Beam treatment systems can be manufactured as trailer-mounted systems, transportable systems, and permanent facilities. Trailer-mounted systems are finished semi-trailers with permanently mounted treatment system components. The existing trailer-mounted system is 48 feet long by 8 feet wide and includes an E-Beam unit with a power rating (accelerating voltage multiplied by beam current) of 21 kW. Trailer-mounted systems are best suited for small-scale, short-term site cleanups and can be used for performing pilot-scale treatability studies.

Skid-mounted, transportable systems can be manufactured and transported to sites on flatbed trucks, where they are off-loaded onto a concrete pad with temporary utility connections and support facilities. These systems can be mobilized and demobilized within a few days. The power rating of transportable systems ranges from 25 to 75 kW. These systems are best suited for medium-scale site cleanups that may last for a few years. Once remediation of a particular site is completed, the transportable system can be moved to another site requiring remediation.

Permanent facilities generally involve high-powered E-Beam systems requiring heavy radiation shielding. These systems are best suited for large-scale remediation projects that require many years of cleanup and for treatment of drinking water or industrial/municipal wastewater on a continuous basis. One large-scale treatment system has been constructed in

Miami, Florida for the treatment of drinking water. This system incorporates an 80-kW beam and has a nominal flow capacity of 120 gpm.

All Haley and Aldrich E-Beam treatment systems are modular in design. Each system includes an electron source, a reaction chamber, water handling equipment, and control components. If the effluent from the E-Beam system does not meet treatment objectives after being treated once, it can be recycled as many times as required until the treatment objectives are met. Haley and Aldrich can also provide treatment trains with multiple modules for treatment of highly contaminated waste streams or large volumes of wastewater. Haley and Aldrich E-Beam treatment systems can be fully automated. This allows remote operation of a system via a computer and telephone line. All operating variables can be continuously monitored by the control console computer to ensure that all system components are operating within acceptable limits.

Haley and Aldrich uses the following three-phase approach in implementing its E-Beam technology for a particular treatment application. During Phase 1, a bench-scale treatability study is performed using a small quantity (2gallons) of wastewater. During bench-scale testing, a ^{60}Co source is used to generate an E-Beam. The purpose of this phase is to determine the effectiveness of the E-Beam process in removing the contaminants of interest and to develop a preliminary cost estimate for full-scale application of the Haley and Aldrich system. During Phase 2, a pilot-scale treatability study is conducted on site using Haley and Aldrich's trailer-mounted system. The results of this study are used to (1) size a full-scale system that can meet treatment goals and (2) estimate the capital and O&M costs for full-scale system operation. During Phase 3, Haley and Aldrich designs and configures the full-scale system.

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7   APPENDIX A: VENDOR'S CLAIMS FOR THE TECHNOLOGY

Hazardous waste treatment and disposal options have traditionally been influenced by regulatory, economic, technical, and public opinion factors. Thus, innovative technologies for remediation of contaminated sites are continually being considered as treatment options. Additionally, from an economic standpoint, the treatment costs of conventional technologies continue to increase, and from an environmental impact standpoint, treatment technologies are being sought that destroy contaminants without creating additional disposal problems.

7.1   Introduction

The E-beam technology has the capability of treating complex mixtures of hazardous waste. The technology draws on the expertise developed from fourteen years and over $8 million worth of research. The result has been the development of a line of hazardous waste treatment systems based on the innovative E-beam technology, which can treat any water, wastewater, or sediment matrix containing toxic organic chemicals and hazardous biological organisms.

7.2   Technology Description

HVEA's E-beam treatment systems use insulated core transformer (ICT) electron accelerators developed by High Voltage Engineering, Inc. In this type of accelerator, the high voltage is produced by a three-phase transformer with multiple secondary windings that are energized by insulated core segments in an iron core. The resulting voltage and current are transferred to an accelerator tube and tungsten wire filament, respectively. The electrons emitted by the tungsten filament are then accelerated by means of voltage differential. Once the accelerated electrons pass through the accelerator tube, they are deflected magnetically (scanned) so as to sweep a larger irradiation field. The scanned E-beam then impacts a flowing stream or slurry, producing highly reactive species capable of destroying toxic microorganisms and organic compounds in aqueous solution. The reactive species formed are $\cdot OH$, e^-_{aq}, and $H\cdot$. The reactions occur at diffusion-limited rates, and the treatment is complete in milliseconds. When the organic compounds are completely destroyed, CO_2, H_2O, and salt are formed as a result.

7.3   Advantages of the E-Beam Process

The HVEA E-beam process has a number of advantages that make it uniquely suitable for use as a treatment process for hazardous microorganisms and organic chemicals. These advantages are described below.

- The process is broadly applicable for the destruction of biological moieties and organic chemicals because strongly reducing reactive species (e-aq and $H\cdot$) and strongly oxidizing reactive species ($\cdot OH$) are formed at the same time and in approximately the same concentrations in solution. Furthermore, the E-beam system is the only treatment technology in which $H\cdot$ is produced.

- Reactions with the E-beam-induced reactive species are very rapid, occurring in milliseconds. This has allowed HVEA to design a flow-through system with good process flexibility at full scale; this system can accommodate flow rates that vary over time. Full-scale systems are modular in design, thereby allowing for decreased operational cost if the quality of the waste improves over time.

- The process can completely mineralize organic contaminants.

- Formation of the reactive species is pH-independent in the range 3 to 11. Therefore, any differences in pH that exist over time do not adversely affect treatment efficiency.

- The process can effectively treat aqueous streams and slurried soils, sediments, and sludges.

- The process is temperature-independent within normal water temperature ranges. The E-beam system is usually housed in a building, and except for the control room, no temperature conditioning is required. Also, variations in water temperature have no practical effect on the treatment efficiency of the process.

- The process produces no organic sludge. The target contaminants are either mineralized or broken down into low molecular weight organic compounds. The process has not been thought to result in removal of heavy metals, but recent studies indicate there may be specific applications.

- The process produces no air emissions. Because this is a water-based technology, no oxides of nitrogen or sulfur are produced. The influent delivery system is closed, and therefore there is no external release of toxic organic compounds.

- For all these reasons, the E-beam process can be used efficiently and effectively as a pretreatment process for biological remediation. The E-beam process can "break apart" complex organic compounds, making them amenable for microbiological degradation.

7.4   HVEA Treatment Systems

HVEA E-beam treatment systems are modular in design. Each system includes an electron source, a reaction chamber, water handling equipment, and control components. This allows for great flexibility in handling contaminated waste streams of differing composition. For example, if a particular waste stream will not meet waste treatment objectives in a single pass using one module, a system can be built to recycle the waste stream as many times as required for complete remediation. Also, single-pass treatment trains with multiple modules can be built to remediate highly contaminated waste streams (ppm to 1% solutions) and to accommodate high flow rates (over 250 gpm). Table A-1 summarizes some of the capabilities of HVEA's treatment systems.

7.5   System Applications

HVEA's E-beam systems are ideally suited for treatment of complex mixtures of industrial and hazardous wastes dissolved or suspended in aqueous media. A partial list of contaminants and pollutants that can be treated using HVEA systems is presented in Table A-2. The general ranges of contaminants in aqueous matrices that can be successfully treated by HVEA's systems are presented below.

- Volatile organics at part per billion levels to 1% NAPLs.
- Semi-volatile organics at part per billion to 1,000-ppm levels.
- Total solids at up to 5% by weight.

Waste streams that can be treated by HVEA's E-beam technology include the following:

- Landfill leachates.
- Contaminated groundwater.
- Contaminated soil.
- Industrial wastewaters from chemical, petrochemical, agricultural, metal finishing, automobile, wood finishing, paint, and pulp and paper plants.
- Drinking water sources.

7.6   Cost Considerations

The cost of treatment using an HVEA E-beam system depends on many factors such as the initial concentrations of organic contaminants, treatment objectives, the dose required to obtain the desired destruction, the volume of waste to be treated, the size of the treatment facility, the length of treatment, and the manner in which capital recovery is handled. The cost of treatment using HVEA systems in various industrial waste and groundwater applications has ranged from $2.00 per 1,000 gallons to $0.50 per gallon. These costs may decrease as a result of economies of scale when more treatment systems are produced in the future. To reduce the required capital investment, HVEA offers turnkey lease options that, for a monthly fee, include equipment, maintenance, and technical services. The minimum lease period is usually 5 years renewable annually, but purchase options are also available. HVEA's leasing arrangements allow for flexibility in responding to changing regulations and changing water quality over the life of a remediation project.

7.7   Summary

HVEA's E-beam system offers an innovative, cost-effective, and flexible technology for treatment of contaminated municipal, industrial and hazardous waters. The technology can treat waters with varying contaminant and feed compositions. The HVEA E-beam treatment system produces a high-quality effluent, destroys complex mixtures of biological and organic pollutants, and can handle waste streams containing solids. This technology has been well demonstrated and is now commercially available for the treatment of a variety of contaminated waters.

Table A-1. Capabilities of HVEA's E-Beam Treatment Systems

Specific Capabilities	Demonstrated Results	Comparison to Conventional Technology
High RE for complex mixtures or pollutants	Routinely reduces organic pollutant concentrations by 99%; pollutant specific	Biological treatment has high Res for biodegradable compounds only; pollutants such as PCBs are not removed
Process can accommodate suspended materials present at concentrations up to 5%	Presence of suspended Kaolin clay has no effect on removal efficiency	Ultraviolet treatment is limited to solutions that are transparent to the ultraviolet source
Significant flexibility to handle changes in feed flow rate and composition	Process is not sensitive to changes in feed pH, temperature, and solids content (up to 5%)	Most treatment systems cannot handle changes in feed composition and still produce a high-quality effluent
Minimal post-treatment needed	E-beam process results in destruction of organic contaminants, which are usually mineralized to CO_2, H_2O, and inorganic salts	Activated carbon and air stripping transfer the contaminants to other media, usually carbon, which have to undergo secondary treatment as hazardous waste

Table A-2. Contaminants and Pollutants Treatable by HVEA's E-Beam Treatment Systems and Other General Uses of the Systems

Organic Contaminants	Biological Contaminants	Other
Aroclors	Biological warfare agents	Color removal
MtBE	Giardia	Odor control
BTEX	*Cryptosporidium parvum*	Bacterial disinfection
Chemical warfare agents	Fecal and total coliforms	Disinfection byproduct removal
Explosives and energetics	*Klebsiella terrigena*	TOC reduction
Halogenated volatiles	PRD1 & MS2 bacteriophages	COD and BOD reduction
Halogenated semi-volatiles	Coliphage	Air or vapor stream remediation
Non-halogenated volatiles		
Non-halogenated semi-volatiles		
Organic cyanides		
Organic pesticides and herbicides		
Phenol and phenolics		
PAH		
Solvents		

7.8 Vendor's comments to the ITER

In response to EPA's comments reflecting E-Beam system performance at the Savannah River Site, it should be noted that the SITE demonstration was conducted before HVEA, Inc. had had an opportunity to optimize their delivery system. The mobile electron beam system fabrication was only completed one week prior to the demonstration and had never been run on any natural water prior to the study. Furthermore, the experimental design for the demonstration that was conducted as Part of the SITE Technology Demonstration, at the Savannah River Site, was written six months before the mobile system had been completed. However, because of the rigid nature of the program and timing constraints placed on the demonstration by the Savannah River Site, HVEA, Inc. was unable to adjust the plan to allow for optimization of the flow (i.e. to increase the dose as was done in this ITER) and therefore it appears that the system was unable to treat TCE and PCE at the concentrations encountered. However, published results have shown that the technology can treat these compounds and several other halogenated compounds, typically found at contaminated sites, to lower concentrations. (Cooper et al., 1993; Mak et al., 1997; Nickelsen et al., 1998).

7.8.1   TOC/DOC Issue

In the demonstration at the NBVC, analytical results indicate that both TOC and DOC concentrations increased significantly from the influent to the effluent. Previous studies with the E-Beam technology have demonstrated a decrease in the TOC concentration as a result of E-Beam treatment. It is believed that the results observed during these pilot tests are artifacts of the analytical methodology utilized.

7.8.2   TOC/DOC Analytical Method Interferences.

Premise: The influent TOC concentration has been underestimated as a result of the analytical method employed. Based on communications with TetraTech, the analytical laboratory used Standard Method 5310B for the analysis of TOC and a modified Method 5310B for the analysis of DOC. According to the method description known interferences are the following: "Removal of carbonate and bicarbonate by acidification and purging with purified gas results in the loss of volatile organic substances. The volatiles also can be lost during sample blending, particularly if the temperature is allowed to rise. Another important loss can occur if large carbon-containing particles fail to enter the needle used for injection…"

Preliminary E-Beam treatment studies conducted by Haley & Aldrich on Port Hueneme groundwater indicated that the groundwater, in addition to MTBE and BTEX, is contaminated with an uncharacterized hydrocarbon fraction. It is assumed that this fraction is comprised of volatile alkane components of gasoline. Based on the chromatograms and resulting calculation sheets, it appears as though the concentration of unknown hydrocarbons is conservatively twice the concentration of the aromatic compounds (BTEX). Based on this estimate and the E-Beam results from the November 2001 tests on Port Hueneme groundwater, an estimate for the TOC concentration can be calculated.

Table 7-1. Estimated TOC Concentration from the Known Contaminant Concentrations.

Analyte	Measured Concn.[a] mg L^{-1}	% Carbon	Calculated TOC Concn. mg L^{-1}
MTBE	1.560	68.12	1.06
TBA	0.133	64.81	0.09
TBF	-	69.72	
Benzene	0.666	92.25	0.61
Toluene	0.812	91.25	0.74
Ethylbenzene	0.204	90.50	0.18
Xylene	0.926	90.50	0.84
Acetone	-	62.04	-
Unknown Hydrocarbons[b]	5.216	85.00	4.43
TOC	**5.1**	-	**7.95**

[a]Third 800 krad unfiltered influent sample.
[b]Twice the sum of the BTEX concentration.

As can be seen in the table the calculated TOC concentration of 7.95 mg L-1 is greater than the measured TOC concentration of 5.1 mg L-1. Presumably this discrepancy is as a direct result of the stripping loss of volatile organic compounds during the acidification and purging steps as described in Standard Method 5310B.

7.8.3 Chemical Transformations During E-Beam Treatment.

It is well known that the E-Beam treatment of volatile organic compounds results in the formation of less volatile, more soluble and more polar organic compounds (i.e., alcohols, aldehydes, ketones, polymers, etc.). An example of this transformation is the formation of phenol from the reaction of benzene with the hydroxyl radical.

In summary:

1. The TOC/DOC analytical method requires acidification followed by purging with an inert gas to remove inorganic forms of carbon.

2. The MTBE plume contains a high percentage of volatile components of gasoline (BTEX, straight chain hydrocarbons, etc.).

3. Treatment of these compounds results in the formation of less volatile/more soluble organic compounds (i.e., alcohols, aldehydes, ketones, polymers, etc.).

Therefore, if one were to purge an influent sample, those volatile compounds would have the propensity to be stripped from solution, whereas, the more soluble/less volatile compounds present in an E-beam treated sample would not purge as readily. This would help explain the observed increase in the DOC/TOC values in the effluent when compared to the influent. The total concentration of organic carbon hasn't really changed but a large portion was purged from the influent samples because of the more volatile nature of the contaminants.

7.8.4 Particulate Losses.

Large carbon-containing particulates may result in underestimating the TOC concentration by preventing entrance into the needle used for injection. During E-Beam treatment these large-carbon containing particulates may be broken down into smaller components and/or the carbon containing organics would be desorbed from the particulate matter. Either situation could result in an apparent increase in the effluent TOC concentration.

7.8.5 Treatment Goals

At the outset of the solicitation for this project there were three groundwaters that were considered for treatment. These three locations were differentiated by their distance from the source and were identified as follows:

1. Source Zone: This zone is closest to the source, contains high concentrations of MTBE as well as benzene, toluene, ethylbenzene, and xylenes (BTEX), and potentially contains free-phase gasoline.

2. Middle Zone: This zone is the area mid-way downgradient along the MTBE plume contains moderate concentrations of MTBE; no BTEX or free-phase gasoline is known to be present.

3. Wellhead Protection Zone: This zone is farthest down gradient along the plume and contains MTBE at lower concentrations than the first two zones.

The original proposal that was accepted for this demonstration was to address the treatment from the Wellhead Protection Zone and was to be treated for drinking water. Prior to the demonstration it was ascertained that the Source Zone was the only area from which adequate water flow could be obtained; however, the treatment goals were not adjusted to take into account the increase in contamination in the ground water.

During the demonstration at the NBVC, the E-Beam technology met the treatment goals based on MCLs for the primary contaminants of concern. However, reaction by-products from MtBE, BTEX and other constituents of gasoline remained in the effluent and were higher in concentration than some potentially applicable ARARs.

Groundwater obtained from the Source Zone would never by utilized as a drinking water source, especially with only one unit process. If groundwater had been extracted from the Middle Zone or Wellhead Protection Zone, where MTBE was the only contaminant of interest, the treatment chemistry would have been different and it is our belief that the analytical results would have shown the E-Beam's effectiveness in meeting all MCLs for both the primary contaminants of concern and their reaction by-products.